



# Evaluation and use of biomechanical parameters for virtual humans walking animations

Benjamin Niay

## ► To cite this version:

Benjamin Niay. Evaluation and use of biomechanical parameters for virtual humans walking animations. Computer Vision and Pattern Recognition [cs.CV]. Université de Rennes, 2022. English. NNT : 2022REN1S053 . tel-03937380

**HAL Id: tel-03937380**

**<https://theses.hal.science/tel-03937380>**

Submitted on 13 Jan 2023

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

# THÈSE DE DOCTORAT DE

L'UNIVERSITÉ DE RENNES 1

ÉCOLE DOCTORALE N° 601  
*Mathématiques et Sciences et Technologies  
de l'Information et de la Communication*  
Spécialité : « Informatique »

Par

« **Benjamin Niay** »

« **Evaluation and use of biomechanical parameters for virtual humans walking animations** »

Unité de recherche : « Institut National de Recherche en Informatique et en Automatique »

## Rapporteurs avant soutenance :

Yiorgos CHRYSANTHOU	Professor, University of Cyprus (CHYPRE)
Nuria PELECHANO	Associate Professor, Universitat Politècnica de Catalunya (ESPAGNE)

## Composition du Jury :

*Attention, en cas d'absence d'un des membres du Jury le jour de la soutenance, la composition du jury doit être revue pour s'assurer qu'elle est conforme et devra être répercutée sur la couverture de thèse*

Examineurs :	Yiorgos CHRYSANTHOU	Professor, University of Cyprus (CHYPRE)
	Brad MCFADYEN	Professor, Université Laval (CANADA)
	Nuria PELECHANO	Associate Professor, Universitat Politècnica de Catalunya (ESPAGNE)
	Nicolas PRONOST	Associate Professor, Université Claude Bernard Lyon 1 (FRANCE)
	Franck MULTON	Research Director, Inria Rennes (FRANCE)
Dir. de thèse :	Ludovic HOYET	Research Scientist, Inria Rennes (FRANCE)
Co-encadrants de thèse :	Julien PETTRE	Research Director, Inria Rennes (FRANCE)
	Anne-Hélène OLIVIER	Associate Professor HDR, Université Rennes 2 (FRANCE)

## Invité(s) :

Prénom NOM	Fonction et établissement d'exercice
------------	--------------------------------------



# ACKNOWLEDGEMENT

---

Ça y'est, cette grande aventure qu'est la thèse touche à sa fin avec ces derniers mots. Trois ans et quelques mois auparavant, je prenais la mer à la recherche de nouvelles terres en naviguant vers l'inconnu. Heureusement, ce voyage a été entrepris avec un merveilleux équipage, qui m'a permis de garder le bon cap et ces quelques lignes sont là pour vous remercier, en espérant n'oublier personne.

Je tiens à remercier évident en premier lieu mes encadrants de thèse. Tout d'abord Ludo, merci d'avoir cru en moi et de m'avoir pris sous ton aile pendant cette aventure. Merci de m'avoir guider, accompagner et me permettre de me développer et d'arriver jusqu'ici. Je te remercie de t'être toujours rendu disponible pour moi ou tes autres doctorants dès que nous avons besoin d'aide que ce soit dans la thèse ou pour d'autres questions. Merci pour ta patience et ta volonté de me faire progresser tout au long de ce parcours. Merci évidemment également à Anne-Hélène et Julien pour avoir épauler comme il se doit Ludo dans cette tâche. Merci à vous trois pour votre confiance, votre soutien, votre patience, mais aussi sens de l'humour et enthousiasme à chaque réunion. Ces trois années auprès de vous m'ont fait énormément grandir que se soit en tant que scientifique mais aussi en tant qu'humain. Je me sens très chanceux d'avoir pu partager ce voyage avec vous et j'espère que beaucoup d'autres auront la chance de pouvoir effectuer un voyage aussi bien accompagné.

J'adresse également toute ma reconnaissance à Nuria Pelechano, Yiorgos Chrysanthou, Brad McFadyen et Nicolas Pronost. Merci beaucoup d'avoir accepté de faire partie de mon jury de thèse, d'avoir évaluer mon manuscrit et pour l'intérêt porter à mes travaux de recherche. Un énorme merci Franck d'avoir accepté de présider mon jury de thèse. Merci également pour tes nombreux conseils et tes incroyables anecdotes racontées autour d'un café.

Merci aux laboratoires Inria et Iria de m'avoir accueilli dans leurs infrastructures. Travailler ici a été un réel plaisir et la liste des personnes incroyables que j'ai pu y ren-

---

contrer est si longue que ces quelques lignes ne peuvent leur rendre tous justice. Merci aux membres des équipes MimeTIC, Hybrid et Rainbow avec qui j'ai partagé tant de choses. Merci aux "anciens", Charles, Georges, Laurent et Marc toujours de bons conseils, toujours le sourire et prêts à nous accompagner pour un café malgré des emplois du temps surcharger. Merci aux moins "anciens" qui m'ont accueilli comme il se doit dès mon arrivée. Merci Olfa, Amaury, Rebecca, Diane, Pierre, Hugo, Charles, Xi, Florian, Fabien et Julien de m'être fait sentir comme à la maison et de m'avoir accompagné dans de nombreuses sorties nocturnes. Merci aux "nouveaux", arriver dans le laboratoire dans ce contexte sanitaire n'a pas été facile pour vous, mais vous n'avez pas baisser les bras et vous pouvez être fier de vous! Merci à Ludo, Anthony, Alberto, Arzhelenn, Louise, Claire, Pauline, Adèle, Thomas, Pierre, Sheryl, Robyn and of course Katja (don't worry I will teach you more useful French words than "la flemme"). Un immense à Nathalie de garder tout ce petit monde sur les bons rails par ta bonne humeur et ta bienveillance! Merci à Laura, pour ta patience à mes milliers de questions. Un grand merci évidemment à Nils et Robin qui ont partagé mon bureau tout ce temps et qui sont toujours là au besoin. Enfin, un grand merci également à Laurence et Sawa, qui ont toujours été d'une incroyable gentillesse avec moi.

La thèse est également une aventure en dehors du laboratoire et pour ça je voulais évidemment remercier mes amis, pour votre soutien et tous les fous rires. Merci Kévin et Julien pour les séances SNK, Smash et soirées crêpes INA ;) Merci à Charlotte, Nico, Manue, Gary, Kelly, Yves, Tristan, Yann, Hippo, Pierre, Rami, Sarah, Antoine, Lilian, Mathieu, Léo et tant d'autres. Merci à vous les colocas, Cindy, Clara et Thérèse d'avoir accepté le Graou et pour votre bonne humeur constante. Merci au club de foot de Saint-Grégoire, qui m'a permis de retrouver motivation et confiance en moi après plusieurs années sans avoir touché un ballon.

Enfin je voudrais profiter de ces dernières lignes pour remercier ma famille. Merci Maman, merci Papa, merci Cyril. Merci tout le monde de m'avoir toujours soutenu et accueilli lorsque je rentrais à la maison. Merci de m'avoir fait confiance et de m'avoir encouragé à faire des études et à supporter mes projets, à continuer à aller de l'avant. Si j'en suis là c'est évidemment en premier lieu grâce à vous et je ne vous remercierai jamais assez.

Encore une fois merci à tous!

# TABLE OF CONTENTS

---

<b>1</b>	<b>Introduction</b>	<b>17</b>
1.1	Context . . . . .	17
1.2	Our approach . . . . .	19
1.3	Contributions . . . . .	20
1.4	Overview . . . . .	23
<b>2</b>	<b>Background</b>	<b>25</b>
2.1	Analysis of Human walking . . . . .	25
2.1.1	Spatio-temporal parameters of human walking . . . . .	26
2.1.2	Invariants of human walking . . . . .	28
2.1.3	Inter individual differences of human walking . . . . .	30
2.2	Synthesis and edition of human walking animations . . . . .	31
2.2.1	Motion capture . . . . .	32
2.2.2	Example-based methods . . . . .	32
2.2.3	Physics-based . . . . .	36
2.3	Perception of human motion . . . . .	38
2.3.1	Perception of biological human motion . . . . .	38
2.3.2	Perception in the context of Computer Animation . . . . .	40
2.4	Conclusion . . . . .	42
<b>3</b>	<b>Walk Ratio: perception of a biomechanical parameter of human walking</b>	<b>43</b>
3.1	Methods . . . . .	45
3.1.1	Stimuli Preparation . . . . .	45
3.1.2	Blend Tree . . . . .	46
3.2	Perceptual experiment . . . . .	48
3.2.1	Participants . . . . .	48
3.2.2	Task . . . . .	48
3.2.3	Experimental Design . . . . .	49
3.2.4	Analysis . . . . .	49

## TABLE OF CONTENTS

---

3.3	Results . . . . .	50
3.4	Discussion . . . . .	53
3.4.1	Perception of the Walk Ratio . . . . .	53
3.4.2	Limitations . . . . .	55
<b>4</b>	<b>Perception of the Walk Ratio: Generalisation and Animation Guidelines</b>	<b>59</b>
4.1	Methods . . . . .	61
4.1.1	Stimuli Preparation . . . . .	62
4.1.2	Task . . . . .	62
4.1.3	Participants . . . . .	64
4.2	Analysis . . . . .	64
4.2.1	Collected Data . . . . .	64
4.2.2	Statistics . . . . .	66
4.3	Results . . . . .	66
4.3.1	Perception of the Walk Ratio . . . . .	66
4.3.2	Eye Tracking Data . . . . .	69
4.4	Discussion . . . . .	71
4.4.1	Perception of the Walk Ratio . . . . .	71
4.4.2	Guidelines for the control of virtual character walking animations .	75
<b>5</b>	<b>Toward editing lower body walking animations based on biomechanical parameters</b>	<b>77</b>
5.1	Poulaine Analysis . . . . .	80
5.1.1	Methods . . . . .	81
5.1.2	Results . . . . .	82
5.1.3	Discussion . . . . .	84
5.2	Reconstruction and Evaluation . . . . .	87
5.2.1	Reconstruction and Objective Evaluation . . . . .	87
5.2.2	Subjective Evaluation . . . . .	91
5.3	Poulaine-based Motion Editing . . . . .	96
5.3.1	Methods . . . . .	97
5.3.2	Task . . . . .	99
5.4	Discussion and Future Works . . . . .	99
5.4.1	Poulaine as a tool to edit motion . . . . .	99
5.4.2	Future Works . . . . .	100

<b>6</b>	<b>Collaboration</b>	<b>103</b>
6.1	Perception of motion variation in large-scale crowds . . . . .	104
6.1.1	Methods . . . . .	105
6.1.2	Results . . . . .	108
6.1.3	Discussion . . . . .	109
6.2	Walking speed and trunk sway: studying the effects of gait features on collision avoidance . . . . .	112
6.2.1	Methods . . . . .	114
6.2.2	Results and Discussion . . . . .	118
6.3	Conclusion . . . . .	121
<b>7</b>	<b>Conclusion</b>	<b>123</b>
7.1	From Analysis and Perception of Walking Animation to Animation Guidelines	123
7.1.1	Experimental Results . . . . .	123
7.1.2	Recommendations to edit walking motions . . . . .	125
7.2	Future works . . . . .	126
7.2.1	Short-Term Perspectives . . . . .	126
7.2.2	Long-Term Perspectives . . . . .	129
	<b>Bibliography</b>	<b>141</b>

# LIST OF FIGURES

---

1.1	Typical crowd from the NBA 2k14 Video Game. Yellow dots correspond to Appearance Clones i.e. characters with similar clothes and character model. Blue dots correspond to Motion Clones, i.e. characters sharing the same animation. Green dots show clones that share both motion and appearance.	18
1.2	In our approach, we combine Motion Analysis and Perception to generate new animations for virtual characters . . . . .	21
1.3	Summary of the main contributions of this thesis . . . . .	23
2.1	Main phases of the walking motion, adapted from Bonnefoy-Mazure and Armand (2015) . . . . .	26
2.2	Step length and step width of the walking motion, adapted from Osoba et al. (2019) . . . . .	27
2.3	Typical hip-knee cyclogram, adapted from Goswami (1998) . . . . .	28
2.4	Ankle trajectory as seen in the hip reference frame, also referred as “poulaine”	29
2.5	Typical point light display stimuli representation of a human walking, adapted from Kern et al. (2013) . . . . .	40
3.1	Xsens Motion Capture system used to record the motion of our actors. The system consists in 17 IMU based sensors (right) placed within a motion capture suit (left). Each sensor is composed of accelerometers and gyroscopes. Figure taken from <a href="http://www.xsens.com">http://www.xsens.com</a> . . . . .	46
3.2	a) Male and female virtual character models used in our perceptual experiment. b) Perceptual experiment set up. c) Example of blend tree for the actor F2, used to output a motion at a specific speed and step frequency (spm: steps per min) . . . . .	47
3.3	(Left) Main effect of Actor on the perceived Walk Ratio: the perceived Walk Ratio was significantly lower for female than male actors. The perceived Walk Ratios were estimated smaller than the captured Walk Ratio, depicted as red diamond, except for Female 2. . . . .	51

3.4	Interaction effect between Actor and Participant Sex on the estimated Walk Ratio. Post-hoc analysis showed that Female 1 was perceived as significantly different from Male 1 and Male 2 whatever the sex of the participant, while Female 2 was perceived as significantly different from Male 1 and Male 2 only by male participants, but not by female participants. . . .	51
3.5	Interaction effect between Actor and Speed on the estimated Walk Ratio. The perceived Walk Ratios were significantly different at 1.0 and 1.2 m/s between Female and Male actors. At 0.8 m/s, only the Walk Ratio of Female 1 was statistically different from the Male actors. For a given actor, there was no difference in the perceived Walk Ratio across speeds. . . . .	52
3.6	Estimated and motion captured Walk Ratios obtained in our study in comparison to previous works of Sekiya et al. (1997) and Zarrugh et al. (1974)	55
4.1	Side view used in the second experiment. The motions were displayed on a treadmill to keep a consistent viewpoint between Screen and Virtual Reality conditions. . . . .	63
4.2	FOVE system used in our head mounted condition (Left) and material used for tracking the body parts most observed by the participants during the VR condition (Right). . . . .	64
4.3	Estimated and captured Walk Ratios for the female (Left) and male (right) actors when their motion is applied on the gender-matched model. An star is displayed when t-test did not find significant difference between estimated and captured Walk Ratios. . . . .	68
4.4	Results of the multivariable linear regression. While actor's height ((a), $p=0.228$ ) and weight ((b), $p=0.667$ ) could not predict accurately the perceived Walk Ratio, the speed of the actor was highly correlated to the perceived Walk Ratio ((c), $p<0.001$ ). . . . .	70
4.5	Percentage of time each body part was looked at by participants and standard error. Each body part is statistically different from one another . . . .	71
4.6	Estimated, Motion captured and Walk Ratios from Sekiya (1997), and Zarrugh (1974) . . . . .	75
4.7	Captured and Estimated Walk Ratios of actors F1, F2, M1, M2 used in the experiments in Chapter 3 and Chapter 4. * significant difference at the 0.05 threshold level, *** significant difference at the 0.001 threshold level. .	76

5.1	Characteristic points used for the analysis of the shape of the poulaine. E corresponds to the maximum extension of the leg, V to the moment where the ankle share the same vertical axis than the hip during the support phase, I to the maximum inflection of the leg, A to the moment when the ankle reaches its maximum altitude and M to the local minima between A and E. . . . .	78
5.2	Ankle trajectory as seen in the hip reference frame (a). This biomechanical parameter is referred as the poulaine, or ankle cyclogram. Longitudinal (b) vertical (c) components of the poulaine. . . . .	79
5.3	Marker set used by Schreiber and Moissenet (2019) to motion capture their subjects . . . . .	82
5.4	Mean poulaine and distribution of the characteristic points when (a) non normalised by the stature of the participant, (b) normalised by the stature of the participant. . . . .	86
5.5	Different reconstructions of the same poulaine using different combinations of control points and interpolation technique. The blue curve corresponds to the original poulaine, the red curve to the reconstructed poulaine and the green dots to the control points used for the reconstruction. . . . .	88
5.6	Root mean square error for each combination of <i>number of control points</i> and <i>interpolation technique</i> , averaged over 20 motion clips from our database.	91
5.7	Viewpoint of the perceptual experiment comparing the different interpolation methods. The framework always consisted in observing both a captured motion and a reconstructed motion, randomly positioned on the left or right	93
5.8	Results of the Perceptual Experiment . . . . .	95
6.1	Examples of virtual crowds stimuli: (left) 250 characters animated with 1 female and 1 male motion, (centre) 500 characters animated with 25 female and 25 male synthetic motions, (right) 1000 characters animated with 500 female and 500 male synthetic motions (i.e. a unique motion per character).	108
6.2	Percentage of correct answers for each <i>Variation Ratio</i> . The chance level ( <i>red</i> ) indicates a statistically random choice. Error bars represent the Standard Error of the Mean. . . . .	110

6.3	Experimental set-up for our pedestrian crossing experiment. (a) Participant equipment set-up with a FOVE head-mounted display, Xsens inertial measuring unit, laptop backpack. (b) and (c): Experimental layout in real world . . . . .	115
6.4	Initial path deviation (square) and clearance distance (dot) investigated in our pedestrian crossing experiment . . . . .	116
6.5	Effect of walking speed condition on Time to contact when participants initiate deviation of their trajectory. . . . .	119
6.6	Effect of walking speed on clearance distance. . . . .	119
6.7	Effect of degree of trunk sway conditions on clearance distance. . . . .	120
7.1	Foule typique du jeu vidéo NBA 2k14. Les points jaunes correspondent aux clones d'apparence, c'est-à-dire aux personnages ayant des vêtements et un modèle de personnage similaires. Les points bleus correspondent aux clones de mouvement, c'est-à-dire aux personnages partageant la même animation. Les points verts indiquent les clones qui partagent à la fois le mouvement et l'apparence. . . . .	134
7.2	Dans notre approche, nous combinons l'analyse du mouvement et la perception pour générer de nouvelles animations pour les personnages virtuels.	137
7.3	Résumé des principales contributions de cette thèse . . . . .	139

# LIST OF TABLES

---

3.1	Summary of the walking speeds achieved by our four actors . . . . .	46
3.2	Interpolated speeds (mean $\pm$ SD) from the blend trees at the different expected step frequencies and speeds, averaged over all four actors' motions.	48
3.3	ANOVA results of the perceptual experiment. Our factors are Actors, Speed, Initialisation (Init.) and Participant Sex (P. Sex). Significant results are displayed in bold, or identified with a $\dagger$ when post-hoc analysis did not confirm the significance of the effect. . . . .	50
3.4	Motion captured and perceived Walk Ratios (m.min), with results of the one-sample student t-test comparing measured and perceived Walk ratios for each actor. . . . .	53
4.1	Actors' summary. . . . .	62
4.2	Main and interaction effects of Actor Sex, Character Gender, Viewing Condition and Participant Gender on the perceived Walk Ratio. Significant results are displayed in bold. . . . .	67
4.3	$p_{tukey}$ values of the post-hoc analysis of the interaction effect between Actor Sex and Character Gender. Significant results are displayed in bold. . . . .	68
4.4	Main and interaction effects of Actor Sex, Character Gender, Viewing Condition and Participant Gender on the perceived normalised Walk Ratio. Significant results are displayed in bold. . . . .	69
5.1	Summary of the actor database used for our analysis. Height, Weight and Body Mass Index (BMI) were significantly different between female and male subjects. . . . .	83
5.2	Regression analysis of each axis component of all the characteristic points using Age, Height, Weight, Gender and walking speed as predictors . . . . .	84
5.3	Regression analysis of each axis component of all the characteristic points normalised by the stature of the actors using Age, Weight, Gender and normalised walking speed as predictors . . . . .	85

5.4	Main results of our method to reconstruct the poulaine from control points and interpolation. . . . .	92
5.5	Main results of our perceptual experiment on the generation of walking leg motions from the poulaine. Significant results are displayed in bold. . . .	94
5.6	Time results of our perceptual experiment. Significant results are displayed in bold. . . . .	94
6.1	Number of unique motions used for each condition. *number of male and female motions were counter-balanced over the experiment in these conditions. . . . .	107

# AUTHOR'S LIST OF PUBLICATIONS

---

## International Conferences

Adili, Robin, **Benjamin Niay**, Katja Zibrek, Anne-Hélène Olivier, Julien Pettré, and Ludovic Hoyet (2021), « Perception of Motion Variations in Large-Scale Virtual Human Crowds », *in: Motion, Interaction and Games*, pp. 1–7.

**Niay, Benjamin**, Anne-Hélène Olivier, Katja Zibrek, Julien Pettré, and Ludovic Hoyet (2020), « Walk ratio: Perception of an invariant parameter of human walk on virtual characters », *in: ACM Symposium on Applied Perception 2020*, pp. 1–9.

## Journals

Bourgaize, Sheryl, Michael Cinelli, Florian Berton, **Benjamin Niay**, Ludovic Hoyet, and Anne-Hélène Olivier (2021), « Walking speed and trunk sway: Influence of an approaching person's gait pattern on collision avoidance », *in: Journal of Vision* 21.9, pp. 2023–2023.

Zibrek, Katja, **Benjamin Niay**, Anne-Hélène Olivier, Ludovic Hoyet, Julien Pettré, and Rachel McDonnell (2020), « The effect of gender and attractiveness of motion on proximity in virtual reality », *in: ACM Transactions on Applied Perception (TAP)* 17.4, pp. 1–15.

## Others

**Niay, Benjamin**, Anne-Hélène Olivier, Julien Pettré, and Ludovic Hoyet (2019), « The Influence of Step Length to Step Frequency Ratio on the Perception of Virtual Walking Motions », *in: Motion, Interaction and Games*, pp. 1–2.

**Niay, Benjamin**, Anne-Hélène Olivier, Katja Zibrek, Julien Pettré, and Ludovic Hoyet (Nov. 2020), « Walk ratio: Perception of an invariant parameter of human walk on virtual characters », *in: Journées Françaises d'Informatique Graphique 2020*, pp. 1–9.

Zibrek, Katja, **Benjamin Niay**, Anne-Hélène Olivier, Ludovic Hoyet, Julien Pettre, and Rachel McDonnell (2020), « Walk this way: Evaluating the effect of perceived gender and attractiveness of motion on proximity in virtual reality », *in: 2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, IEEE, pp. 169–170.

Zibrek, Katja, **Benjamin Niay**, Anne-Hélène Olivier, Ludovic Hoyet, Julien Pettré, and Rachel McDonnell (2022), « Proximity in VR: The Importance of Character Attractiveness and Participant Gender », *in: IEEE VR 2022-IEEE Conference on Virtual Reality and 3D User Interfaces*.



# INTRODUCTION

---

## Contents

<b>1.1</b>	<b>Context . . . . .</b>	<b>17</b>
<b>1.2</b>	<b>Our approach . . . . .</b>	<b>19</b>
<b>1.3</b>	<b>Contributions . . . . .</b>	<b>20</b>
<b>1.4</b>	<b>Overview . . . . .</b>	<b>23</b>

---

## 1.1 Context

Walking is one of the most common task performed by humans, to move from one place to another. It does not require specific skills or equipment, and provides a daily sport activity for billions of people. Every day we are surrounded by people walking to their destination, sometimes alone, sometimes as a group. While it is common to see groups of people walking at the same speed to be able to chat together when going out of a stadium after a sports event or entering a theater, it is unlikely that they also share the same morphological attributes and especially if the number of walkers in the group increases. In such scenarios, people share a common path and goal a brief moment but with their own characteristics (e.g., age, morphology, mood) and walking patterns.

While we are used to this diversity in real-life crowd scenarios, entertaining applications still struggle to replicate the complexity of walking crowds. Ideally, every character in a video game or a movie should look and behave as a unique entity when presented on a screen to produce realistic characters and thus lively and spectacular scenes. To replicate this diversity, the most straightforward technique used by the movie industry is to recruit and coordinate as many extras as required for a specific scene, counting from a few individuals to hundreds of thousands, leading to a logistical nightmare for directors. For instance, over 300 000 extras were recruited for shooting a less than 4 minutes long scene in the movie Gandhi (1982). With the improvement of computer



Figure 1.1: Typical crowd from the NBA 2k14 Video Game. Yellow dots correspond to Appearance Clones i.e. characters with similar clothes and character model. Blue dots correspond to Motion Clones, i.e. characters sharing the same animation. Green dots show clones that share both motion and appearance.

graphics capabilities, crowds can now be recreated in a virtual environment to be included afterward during post-production, improving undeniably the capacity to create quickly basic crowds. However, the diversity and appealing aspect of the crowd is often lost as individualising appearance, motion and behavior of each virtual character requires tremendous amount of resources and is therefore often not feasible. A common strategy to reduce such costs is to duplicate the assets of a few characters (in terms of appearance, pose, motion) to multiple characters on screen, which leads to a certain uniformity in the crowd and diminishes its naturalness as can be seen in Figure 1.1. In this figure, we can clearly observe some characters wearing the same outfit and having the same facial model, they are referred as *appearance clones* (yellow dots in Figure 1.1). We can also distinguish characters having a different appearance but sharing a similar pose at this frame, suggesting that they have the same animation and thus motion within the application. Such clones are referred as *motion clones* (blue dots in Figure 1.1). We can even observe clones sharing both the same appearance and the same motion (green dots in Figure 1.1). All these clones confer to an application a certain uniformity that reduces drastically the involvement of the user. To reduce this feeling of uniformity, the easiest way is to play with appearance and motion clones and control precisely their number and position on the scene to avoid observers spotting them (McDonnell et al. 2008).

Other troublesome effects can occur when duplicating a motion on a virtual character with significantly different morphological or individual properties. For instance animating an elderly fragile woman with the motion of a very young muscular individual might seem uncanny to the observer’s eyes. Thus, there is a clear need for virtually populated applications to reduce their uniformity while keeping coherent behaviours. In particular, such applications require to add variations across the characters, in terms of appearance and motion. While some guidelines have been provided to increase variation in characters through appearance (McDonnell et al. 2008; McDonnell et al. 2009c), motion variation still suffers the need of tremendous amounts of manual artistic work. Techniques focused on editing existing motions to generate variations of these motions are thus valuable for the computer graphics community. However, such existing techniques mainly focus on statistical variations of motions which often lack of precise control on the output motions which can lead to incongruousness between the appearance and the motion of the characters.

In this thesis we are interested in exploring how to bring variations in virtual humans through motions. More specifically, we will focus on walking, one of the most commonly used motion in interactive applications. We will investigate how to easily generate walking motions that are not only realistic, but also adapted to specific character features to populate environments with characters that display different motions that are congruent with their individual characteristics (e.g., age, gender, height). More specifically, we want to use biomechanical parameters of human walking motions to control and edit walking animations. Using biomechanical parameters of human walking seems promising to us as they often represent simple characteristics (e.g., step length, step frequency, walking speed) to tune for animators and have been widely studied in the human motion literature.

## 1.2 Our approach

This thesis deals with the creation of walking motions that are specific to an individual’s characteristics in order to create virtual characters’ walking motions that look visually varied. However, adding variations is a challenging task and raises many questions. What is variation? How much variation is needed? Where should we put the variation? Is the variation perceived by observers? Do the variations bring unnatural motions perceived by observers? Answering these questions requires to understand and study different research topics. First, we want to understand what makes one’s motion unique, depending

on various demographics and anthropometrics features (e.g., age, gender, height, weight). The research field dealing with this questioning is referred as **Motion Analysis**. More specifically, we focus on invariant parameters of human walking motion and its modelling to propose methods to generate and modify walking motions that are adapted to a specific set of actors' characteristics in an automatic and fast manner.

In particular in this thesis, we adapt existing **Motion Synthesis** techniques (Motion Blending, Inverse Kinematics) with our motion analysis findings to synthesize walking animations that are adapted to actors' characteristics.

While combining both motion analysis and motion synthesis enables us to generate walking animations that are faithful to the biomechanical laws of motion, they do not ensure that observers perceive these animations more appealing or realistic than the ones generated through traditional motion synthesis techniques. We can also wonder which actors' characteristics or body parts are influencing the most how varied a scene with walking characters is. Additional questions raise as well, for example related to the quantity of variations needed to break the uniformity of a scene, or about the relative importance of appearance and motion on the variety of a scene. To answer these questions, we propose methods derived from the **Perception** field. In particular we conduct user studies where participants are asked to evaluate the realism of walking animations controlled through different parameters.

In this thesis, we thus propose an approach combining these three research topics (see Figure 1.2). In particular, we build on the analysis of walking motion from a biomechanical point of view to propose frameworks to edit walking animations. We then evaluate the relevance of our frameworks through user studies in which we fully investigate how to efficiently use these frameworks for character animation.

## 1.3 Contributions

This thesis presents three main contributions based on three different experimental studies. As a first contribution (Chapter 3), we explore the relevance of a kinematic variable of human walking for generating and editing walking animations. This variable, named the Walk Ratio (WR), is defined as the ratio between step length and step frequency and has been studied in the biomechanical literature. It has however never been used in animation, while presenting potentially interesting characteristics for controlling human walking animations, such as invariance across speeds for a given individual, as

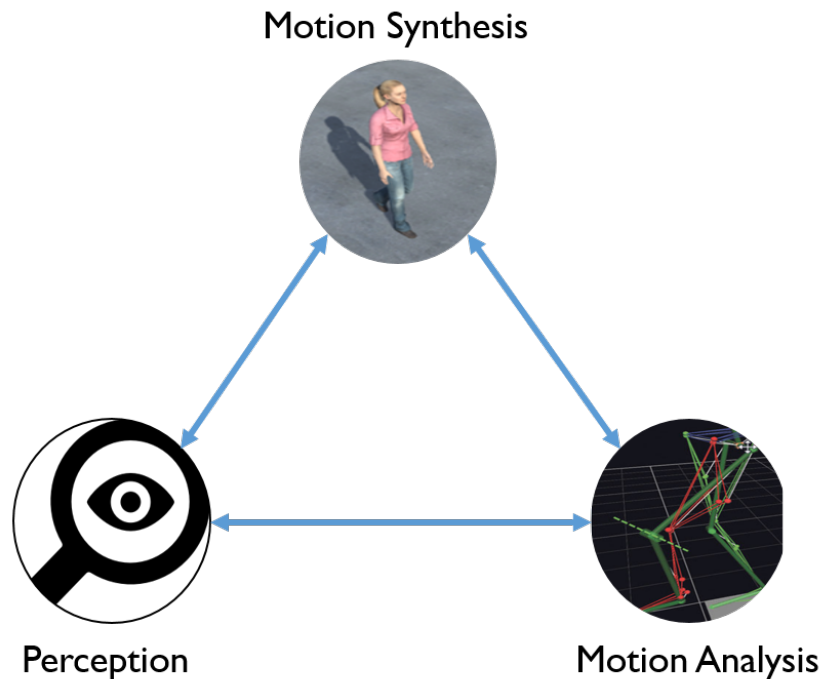


Figure 1.2: In our approach, we combine Motion Analysis and Perception to generate new animations for virtual characters

well as differences related to gender, morphology and age. To investigate its relevancy in computer animation, we carried out a perceptual experiment in which participants had to modify the walking motion of virtual characters playing on their step frequency, which modifies the Walk Ratio. In particular, they were presented with motions at different step length and frequency combinations while keeping a constant walking speed. As speed is the product of step length and step frequency, modifying one of these parameters was automatically modifying the other to keep the same speed. Participants could modify the step frequency and thus the step length of displayed motions until they chose the combination of these two parameters that was the most natural in their opinion. The step length to step frequency ratio of the chosen combination was the estimated Walk Ratio for each virtual character presented to the participants, which we compared to the natural (captured) Walk Ratio of the corresponding actors whose motions have been used in our experiment. Our results showed that observers estimate Walk Ratios that are in the range of natural Walk Ratios depicted in the biomechanical literature. We found gender differences in the perception of the Walk Ratios, but invariance across speeds for a given actor which is also in agreement with the biomechanical literature of the Walk Ratio. This

work was accepted and presented at the ACM Symposium on Applied Perception 2020 (Niay et al. 2020).

This first contribution was the first study to explore the potential use of the Walk Ratio for computer animation purposes. For this reason, this first study was limited to a small number of actors (4). We therefore decided to extend this contribution in a second experiment (Chapter 4), to evaluate whether our results would generalize across a larger number of actors (16). This enabled us to explore other factors that could affect the perception of the Walk Ratio, such as actor gender, height, weight or walking speed. In this contribution, we also explored other perceptual factors by displaying the motions on a gender-matched and a gender-mismatched character model to explore whether the perception of the Walk Ratio was more influenced by motion or appearance, as well as and using both Virtual Reality (VR) and a traditional screen to present the stimuli to the participants. Our results showed that gender, height and individual walking speeds were associated with significantly different Walk Ratio. We also did not find an effect of the appearance of the character (gender-matched or gender-mismatched model) and display condition (screen or VR) on the perceived Walk Ratio. The first and second contributions demonstrate that the Walk Ratio has the potential to be used to control and edit walking animations of virtual characters while ensuring the naturalness of motions.

In a third contribution (Chapter 5), we investigated the use of the *poulaine*, another kinematic variable characterizing human locomotion, to edit leg walking animations. The *poulaine* corresponds to the trajectory of the ankle as seen in the hip reference frame. We propose a three-step approach. First we analyse how the shape of the *poulaine* is influenced by individual characteristics. Then we propose a reconstruction method of the lower body motion based on the *poulaine* and provide ways of modifying the *poulaine* according to desired individual characteristics. Finally, we propose a framework to evaluate our reconstruction method through a perceptual experiment in which we compare our method with other state-of-the-art approaches.

A summary of the different contributions can be found in Figure 1.3

Finally, Chapter 6 presents several collaborative works I have been involved in during my PhD, on topics related to variety in crowd animation and pedestrian collision avoidance. More specifically, we investigated the number of motions required to obtain a crowd that look more varied than a crowd animated with a unique motion (Adili et al. 2021). For this collaboration, I was mainly involved in the different research discussions as well as in the supervision of the master student who conducted the study. In a second collaboration,

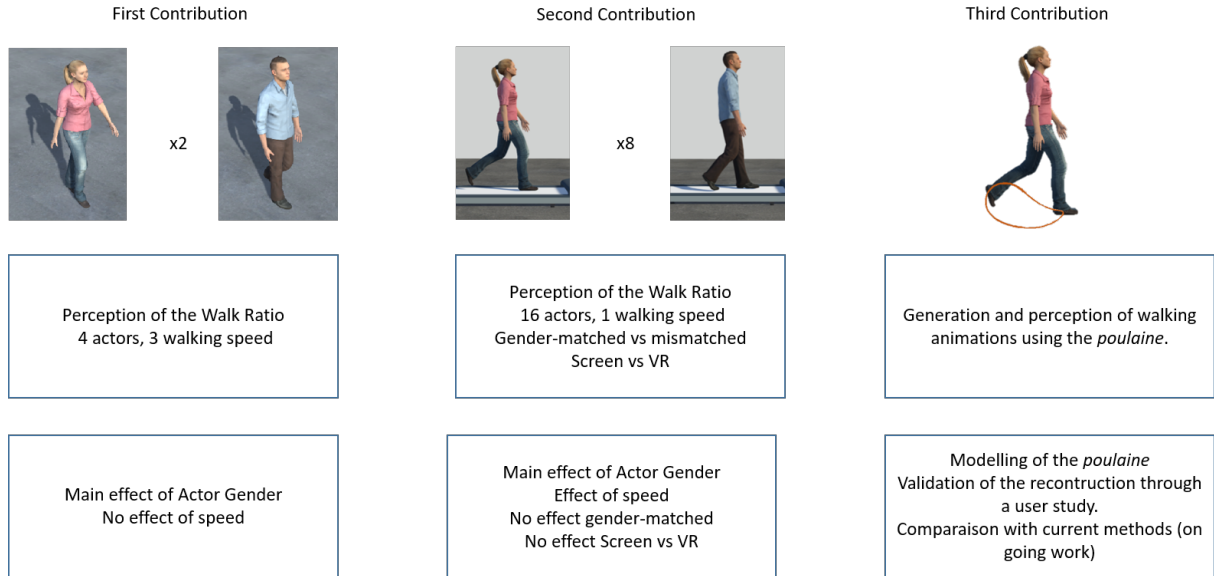


Figure 1.3: Summary of the main contributions of this thesis

we explored the effect that other gait parameters (degree of trunk sway and walking speed) may have in a slightly different context, related to pedestrian collision avoidance. More specifically, we explored the influence of these two parameters on the avoidance strategy of participants when crossing a pedestrian in Virtual Reality (Bourgaize et al. 2021). For this collaboration, I was mainly involved in the experimental aspects by designing and conducting the experiment.

## 1.4 Overview

This thesis is structured as follow, Chapter 2 presents the state of the art in related topics of human walking motion analysis, its synthesis in the computer graphics community and how biological motion is perceived by observers. Chapter 3 introduces a first study on the perception of a biomechanical parameter of human walking, the Walk Ratio, which had never been studied in the context of Character Animation and which presents interesting individual specific characteristics, when applied on virtual characters. We extend the study of this parameter in Chapter 4 where we assess additional parameters potentially affecting its perception. Chapter 5 investigates the use of another parameter of human walking to generate walking animations as well as its perception. Chapter 6 explores the quantity of variations to add when dealing with large group of characters,

and other gait metrics that can influence observers' perception and behavior in two collaborative works. Finally, Chapter 7 presents a general conclusion of these contributions and future perspectives.

# BACKGROUND

## Contents

<b>2.1</b>	<b>Analysis of Human walking . . . . .</b>	<b>25</b>
2.1.1	Spatio-temporal parameters of human walking . . . . .	26
2.1.2	Invariants of human walking . . . . .	28
2.1.3	Inter individual differences of human walking . . . . .	30
<b>2.2</b>	<b>Synthesis and edition of human walking animations . . . . .</b>	<b>31</b>
2.2.1	Motion capture . . . . .	32
2.2.2	Example-based methods . . . . .	32
2.2.3	Physics-based . . . . .	36
<b>2.3</b>	<b>Perception of human motion . . . . .</b>	<b>38</b>
2.3.1	Perception of biological human motion . . . . .	38
2.3.2	Perception in the context of Computer Animation . . . . .	40
<b>2.4</b>	<b>Conclusion . . . . .</b>	<b>42</b>

## 2.1 Analysis of Human walking

Locomotion can be defined as the ability of a living organism to move from a starting to an end point. For Humans, various locomotion means can achieve this purpose, some only require human capabilities (walking, running, swimming) while others require to ride a vehicle (cycling, canoeing). From all the variety of locomotion means used by humans, walking is the most performed and enabled them to navigate diverse environments. Therefore it has been widely studied across centuries, from simple visual observation in its early stages to more advance analyses recently. In this thesis, we are interested in generated walking animations that are specific to actors' characteristics. Thus, in this section, we will first define how human waking is analyzed by investigating its spatio-temporal parameters. Then, we will analyse the different invariant parameters of human walking, as

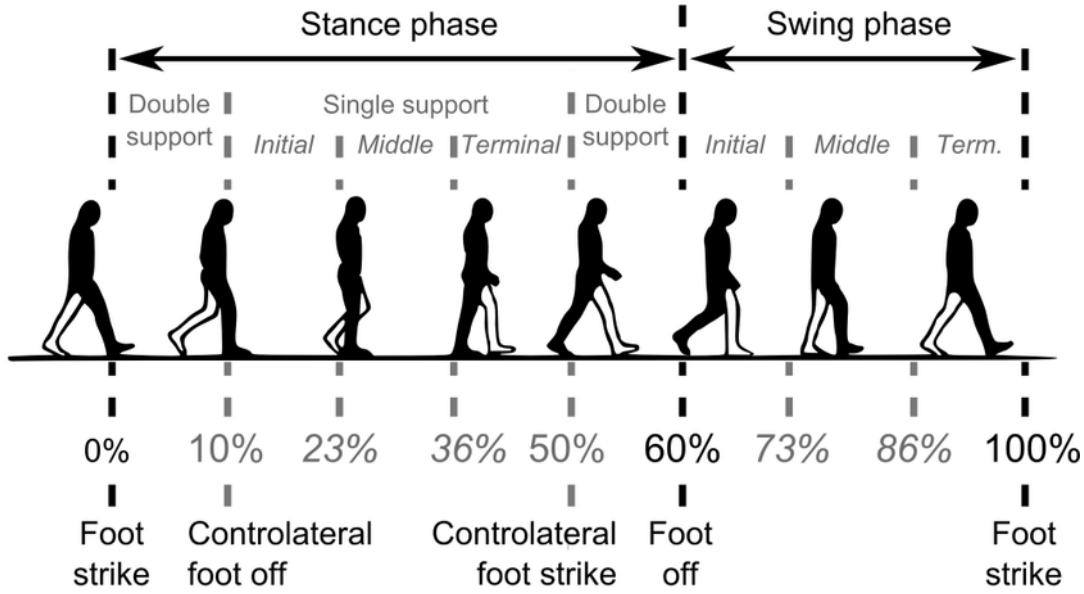


Figure 2.1: Main phases of the walking motion, adapted from Bonnefoy-Mazure and Armand (2015)

understanding the parameters which are essential for a human to walk is key for modelling walking motion with a subset of parameters. Finally, we will study how the walking motion pattern is influenced by several parameters specific to individuals.

### 2.1.1 Spatio-temporal parameters of human walking

Walking is a cyclic motion (Gage 1990) (see Figure 2.1) consisting of four subtasks (Woollacott and Tang 1997): (1) generation of continuous movement to progress toward a destination, (2) maintenance of equilibrium during progression, (3) adaptability to meet any changes in the environment or other concurrent tasks, and (4) initiation and termination of locomotor movements. Thus, human can move by repeating a specific movement: the step. The step is the succession of events occurring between the strike of one foot to the strike of the other foot, the succession of two steps is referred as a stride. The length of a step, or step length is the distance between one point of the foot and the same point of the other foot at a strike event on the longitudinal axis. Step width corresponds to the distance between one point of a foot and the same point of the other foot on the next stride on the mid-frontal plane. These two spatial parameters are represented in Figure 2.2. On the temporal basis, walking can be analyzed through its cyclic nature. A gait cycle is the time between one event of a foot and the same event of the same foot

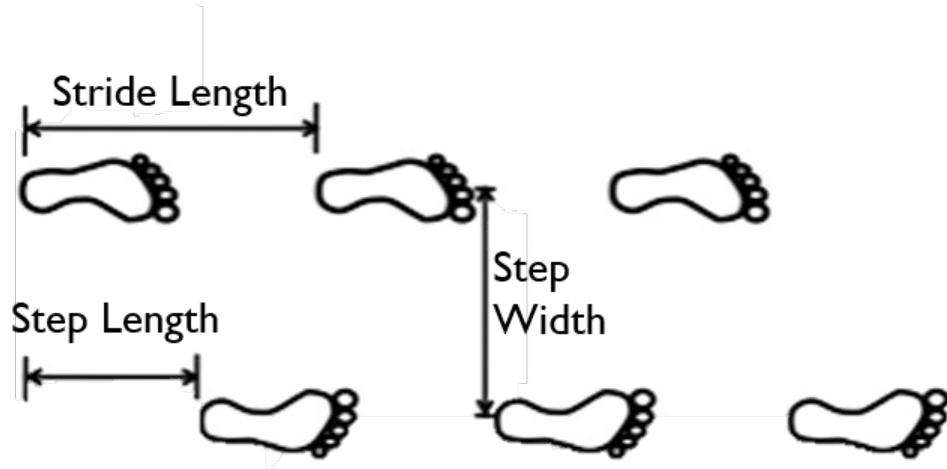


Figure 2.2: Step length and step width of the walking motion, adapted from Osoba et al. (2019)

during the next stride. Although, any moment of the gait cycle can be used, researchers commonly use the foot strike as a starting and ending point. The gait cycle can then be represented as a percentage, with the foot strike of the same foot being the 0% and 100% of the cycle (see Figure 2.1). The cycle is generally divided into two phases, the stance phase which represents 60% of the cycle and the swing phase which represents 40% of the cycle. The inverse of the duration of a gait cycle is the stride frequency and half this duration is the step frequency. Step length ( $SL$ ) and step frequency ( $SF$ ) are important parameters of human walking. Combined with step frequency ( $SF$ ), which is the inverse of the duration of a step (i.e. half a stride), we can obtain the walking speed ( $v$ ) of an individual (Andriacchi et al. 1977):

$$v = SL.SF \quad (2.1)$$

Thus human walking have been mainly studied in the world reference frame. However, researchers also proposed to study this cyclic as seen in the subject point of view. For example, Grieve (1968) proposed to study joint angles in relationship from one another rather than studying them individually against time in a typical “cyclogram” representation (see Figure 2.3) and have been used to study limb coordination (Awai and Curt 2014). Ankle cyclogram, which represent the trajectory of the ankle as seen in the hip

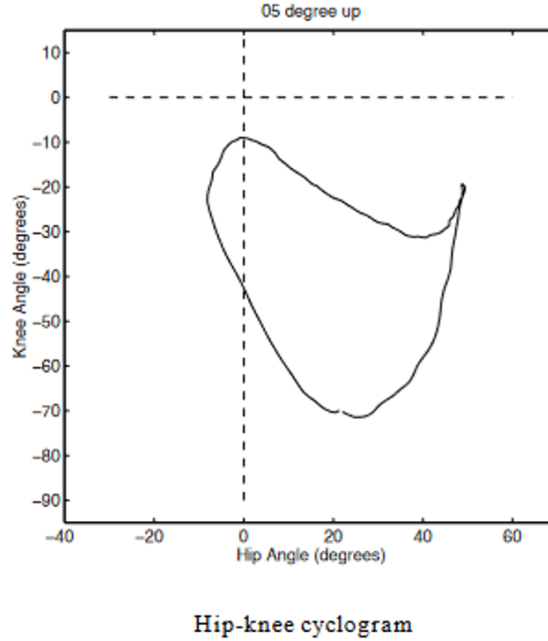


Figure 2.3: Typical hip-knee cyclogram, adapted from Goswami (1998)

reference frame (Decker et al. 2006; Laumond et al. 2017) also been proposed to study the human cyclic motions, such as walking or running. This representation possesses a specific shape as seen in Figure 2.4 and is further presented in Chapter 5

In the following subsections, we explain why this locomotion task produces intra-individual variability while reaching such inter-individual differences.

### 2.1.2 Invariants of human walking

As we explained above, human walking motion can be described through spatio-temporal parameters. However, these parameters can vary according to several factors, as we will described in the next section. Thus, to be able to compare the walking performance of individuals with different characteristics, studies in human motion focused on representing this motion as invariants parameters which we analyze here.

As explained previously, walking is composed of 4 subtasks, including moving forward and keeping balance. Das and McCollum (1988) highlighted these two tasks as invariants of human walking. Based on this definition, researchers assumed that these invariant subtasks are dependent on mechanisms that are invariant to produce low intra-individual variability. In particular, Borghese et al. (1996) proposed to study the elevation angles

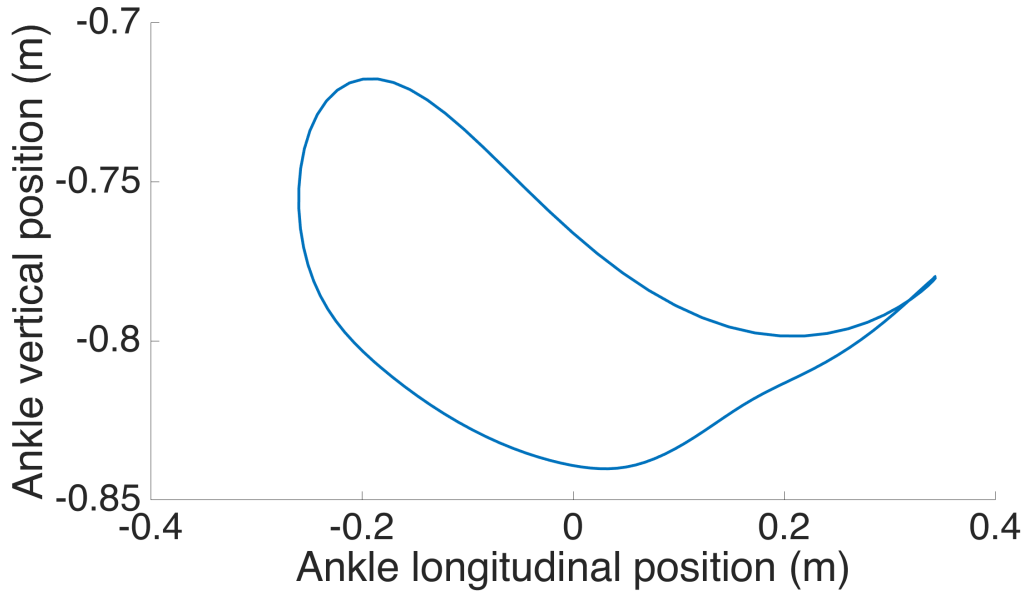


Figure 2.4: Ankle trajectory as seen in the hip reference frame, also referred to as “poulaine”

of the lower limb in relationship from one another. They found that the time course of the changes in the angles of elevation of lower limb segments relative to the vertical was presenting a similar pattern across subjects and the changes of the thigh, shank and foot elevation covaried along a plane during the whole gait cycle. This representation have been demonstrated invariant across speeds (Borghese et al. 1996), when walking forward and backward (Grasso et al. 1998) and is highly correlated with energy expenditure (Bianchi et al. 1998).

We also previously explained that walking speed was the product of step length and step frequency (Andriacchi et al. 1977). As a result, a infinite combination of step length and step frequency is theoretically possible to achieve a given walking speed. However, humans are unlikely to select very long steps at a short step frequency, or very small steps at a very high step frequency. Indeed, to minimize energy expenditure, humans tend to select a specific combination of step length and frequency (Ralston 1958; Zarrugh et al. 1974). The ratio of these two specific is defined as the Walk Ratio (Sekiya et al. 1996). More interestingly, this ratio is invariant at different walking speeds for a given individual (Terrier and Schutz 2003; Murakami and Otaka 2017), only varying at very high (Murakami and Otaka 2017) and lower walking speeds (Sekiya et al. 1996; Terrier and Schutz 2003). It has also been showed invariant even with several months separating the measures (Sekiya and Nagasaki 1998). Finally, Terrier and Schutz (2003) demonstrated

that while the intra-individual variability of the Walk Ratio was low (1 to 4%), the inter-individual variability reaches values around 10%.

Other invariants in human walking have been highlighted in the literature but are out the scope of this thesis, we thus briefly introduce the reader to such invariants. For instance, the speed-curve power law is an invariant of motion which governs curve trajectories (Viviani and Terzuolo 1982; Zago et al. 2018). In terms of muscular activity, Lim et al. (2013) demonstrated that joint kinematics, joint moments and muscle contributions to the Center Of Mass (COM) accelerations were invariant between healthy young and older adults when walking at the same speed.

These invariants parameters of walking explains why humans present very few variations intra-individually, however we still need to understand how and why walking motion varied from one individual to another.

### **2.1.3 Inter individual differences of human walking**

As seen in the previous subsection, some human walking parameters remain invariant across individuals. However, other gait characteristics are connected to different parameters.

Spatio-temporal parameters have been widely studied in the biomechanical community. In particular, gait speed is considered as the sixth life-sign in humans. Thus, early focus has been made on comparing gait characteristics of healthy and pathological walking subjects, such as of Parkinson (Paker et al. 2015), Stroke (Goldie et al. 1996), Multiple Sclerosis (Givon et al. 2009) or Unilateral vestibular neurotomy (Borel et al. 2004), which have all been associated with lower gait speeds.

However, other individual characteristics have been reported to impact one's gait. In particular, age has been shown to be a great predictor in human walking. Young adults typically walk faster than older adults at comfort (Frimenko et al. 2014; Rowe et al. 2021) and faster walking speeds (Bohannon 1997), in both forward and backward motions (Laufer 2005). The elderly perform shorter steps while maintaining a similar step frequency than young adults to reduce the risks of falling (Winter et al. 1990; JudgeRoy et al. 1996). For children the pattern is a bit different, while 7 years old achieved similar walking speed than young adults, they usually perform shorter step length but a higher step frequency (Ganley and Powers 2005; Gouelle et al. 2016).

Gender is also a parameter that can potentially affect the spatio-temporal parameters of walking, although more ambiguous. Frimenko et al. (2014) examined gait speed data

of 47 studies which informed male and female walking data. They noticed that around 17% of the studies reported statistically significant sex differences in the 20 - 59 years old age range, while this number increases to more than 30% for the 60 to 99 years old range. Their results suggest that female walking speed decreases more with age compared to male walking speed. In the studies pointing gender differences, results indicate that female walkers tend to perform shorter steps at a higher step frequency than male walkers while maintaining a similar speed (Kerrigan et al. 1998).

Other researches pointed out that the sex differences highlighted in the literature may be more linked to morphological differences than to actual male/female differences as, when normalized by body dimensions, the differences previously observed tended to disappear (Bruening et al. 2020). Thus, the previously reported sex differences may be partially explained by height and weight differences between female and male walkers (Senden et al. 2012; Camarri et al. 2006).

To evaluate whether height or gender influence the most walking motion, some studies predicted lower limb kinematics by performing mixed-effects linear regression (Chehab et al. 2017) or multilinear regression (Moissenet et al. 2019) from walking speed and different demographic features age, sex and body mass index (BMI). They both demonstrated that walking speed have more influence in predicting gait kinematics than demographic features. Finally, emotion has also been highlighted as a feature that influences kinematic variables of human walking motion. More specifically, emotion has a strong influence on walking speed (Barliya et al. 2013) with humans walking faster when joyful or angry, and slower when sad (Gross et al. 2012).

In this section, we presented the different characteristics of the human walking motion. First, we presented the different spatio-temporal parameters of the human walking motion, then we investigated the different invariants of this motion before presenting features influencing human walking motions. Now that we know how humans walk, we will focus in determining how to synthesize it for virtual characters.

## **2.2 Synthesis and edition of human walking animations**

Generating synthetic human motions has been a very important research topic for different applications, ranging from a hyper realistic character suited for virtual reality and other immersive environments, to more generic motions to apply to groups of characters

that need to move in a crowd scenario. In this section, we cover the different techniques used to generate and modify human motions.

### 2.2.1 Motion capture

The most straightforward method to animate a virtual character with realistic human like motions is to capture them from a real actor. With the multiplicity of motion capture systems and techniques comes an increase of data available to animate characters. The recording of the motions can be performed with different systems, each presenting advantages and disadvantages. Opto-electronic and Inertial Measurement Units (IMU) systems are the most spread in the biomechanical and computer graphics community. The former consists in tracking the trajectories of reflective markers positioned on the subject's body with infrared cameras. The latter combines accelerometers, gyroscopes and magnetometers placed on the subject body to compute the position and orientation of the subject's joints. Although these tracking systems provide precise and natural information of the human motion, errors can occur due to occluded markers, noise at higher frequencies, jitter or mislabelling of markers that algorithms try to fix (Burke and Lasenby 2016; Holden 2018). It is also required to correct the animation for the shape of the subject, a process which is called motion retargeting (Gleicher 1998). Indeed, virtual characters are animated using a simplified structure, while the motion capture data encodes the motion of the shape of the actor subject requiring the use of additional computing to adapt the recorded motion to an animation (Holden 2018; Chen et al. 2021). Nevertheless, motion capture systems have the main advantage of capturing the naturalness of the actor's own motions and style. One of the main drawbacks of only relying on motion capture is that the higher number of characters we want to animate, the more motion capture data is needed. This can lead to tremendous amounts of recording time, data processing and storage costs. Thus, being able to modify existing recorded motions to avoid these issues is critical in computer animation, and different families of techniques have been proposed over the last two decades.

### 2.2.2 Example-based methods

While the amount and quality of motion capture data increased with the improvement of motion capture systems, researchers also focused on editing the existing motion library to enhance their use for computer animations. These techniques use example motions to

modify and generate new motions and can be regrouped into different subfamilies.

### **Constraint-based**

Constraints-based methods provide both an intuitive and high level control over the motion of the virtual character. The overall idea of the techniques based on constraints is to preserve the interaction between the character and its environment, for example preventing the feet of interpenetrating the floor. One of the most common technique to guaranty such interaction is Inverse Kinematics. Inverse Kinematics is very common in different research topics such as robotics, biomechanics or computer animation. It consists in finding all the angular configuration  $q$  (in angular coordinate system) of a kinematic chain that satisfies a constraint  $X$  (in cartesian coordinates system). Thus, the objective is to find the inverse function that satisfies the following equation:

$$f(q) = X \Rightarrow q = f^{-1}(X) \quad (2.2)$$

This can be performed analytically when the number of degrees of freedom is low enough to have simple equations (Kulpa et al. 2005; Kallmann 2008; Li et al. 2021), or by optimisation methods (Buss 2004). Constraint-based methods offer the possibility to generate motions based on high level controllers such as step length at rather low time and computational costs for simpler models. However, inverse kinematics suffers two main issues. First, it has difficulties to deal with multiple tasks at the same time and second, the quality of the model will dictate the quality of the resulting motions which is hard to predict beforehand. In a similar , it is also possible to rely only on Lagrangian approaches to deform animations based on constraints, either with other characters (Ho et al. 2010) or with the environment (Al-Asqhar et al. 2013).

### **Motion Blending**

Motion blending is a family of techniques developed to generate motions from examples. The main idea is to blend similar motion examples, obtained through motion capture or key frame animation, according to weights to generate a new intermediate motion with the desired characteristics. The main advantage of this technique is that it allows to handle multiple complex tasks at the same time. In particular, motion blending can be used in different motion tasks, such as grasping while satisfying specific spatial constraints (Aydin and Nakajima 1999). In the context of walking animation, blending

provides a high level control of the output motion in terms of spatio-temporal parameters by manipulating the blending weights accordingly (Park et al. 2002; Basten et al. 2011). It also offers the possibility to generate different styles for a given walking motion (Rose et al. 1998). Feng et al. (2012) indicate that several algorithms have been proposed to blend between the motions: Barycentric (Beacco et al. 2015), K-Nearest-Neighbor (Allen et al. 2002; Gaisbauer et al. 2018), Radial Basis Function interpolation (Rose et al. 1998) or inverse blending (Huang and Kallmann 2010). However, no single blending technique is perfect for every task, and it often requires the need of a large input database and can lead to unnatural motions when blending is not performed correctly (Safonova and Hodgins 2005; Wang and Bodenheimer 2004; Wang and Bodenheimer 2008b).

## **Motion Graphs**

As explained above, blending can lead to unnatural motions if not performed correctly. To overcome this issue, Kovar et al. (2002) proposed to use poses instead of full motions to synthesize streams of motions. In particular, they represented simple motions clip as graphs, composed of nodes (poses) and edges (transitions between the poses). The motion graph computes the similarity between two poses of different clips, to allow a smooth transition. Initially they proposed to use the distance between joints to compute the similarity between two poses, however several studies proposed other methods to better compute the distance between two poses, by comparing joint angle and joint velocities (Lee et al. 2002; Wang and Bodenheimer 2003), torso velocity and acceleration in the local coordinate system (Arikan and Forsyth 2002), or by modelling a probabilistic distribution function using Gaussian Processes (Min and Chai 2012). By first computing offline all the possible transitions between the motions, a new motion is then generated by finding a path in the graph that selects the optimum transitions according to specified goals (e.g., trajectory to follow, position to reach). Characters can thus perform different walking styles and speeds by navigating in a graph containing varied motions clips. Even though they produce high quality motions at run time, motion graphs are still dependent of a large input database to perform very specific tasks.

## **Statistics-based**

Statistics-based methods are focused on modelling the general behaviour of a specific task based on large motion database. The main purpose of these techniques is to generate motions with variations rather than to adapt motions to specific constraints. Most of the

techniques include a learning step to capture the different properties of an input database, which can be achieved using several statistical models. Brand and Hertzmann (2000) learnt a Hidden Markov Model to generate variations of a specific action by interpolating or extrapolating learnt styles. Grochow et al. (2004) used a Scaled Gaussian Process Latent Variable Model to learn an inverse kinematics system. Lau et al. (2009) pioneered the use of Bayesian networks to model both spatial and temporal variations of an input database, while Ma et al. (2010) use it to model both style and variation of an input database. Statistics-based methods are very useful to generate tremendous amounts of similar but different motions, but they struggle at adapting to characters with characteristics that differ from the input database and often require extra processing cleaning steps (Ikemoto et al. 2006). Furthermore, controlling the specific desired motion is very difficult with these approaches because of their non-linearity.

### **Deep-learning based**

Recently Deep Learning techniques emerged as popular tools in a wide range of applications including computer animation. Frameworks based on deep learning automatically learn the desired features from the dataset, increasing their popularity for synthesizing novel data from the model. Thus, several studies proposed to apply deep learning to human motion capture data to synthesize motion. Early works focused on applying conditional Restricted Boltzmann machines to synthesize gait animations (Taylor and Hinton 2009; Taylor et al. 2011). More recently, Holden et al. (2016) proposed a deterministic generation of human motion by representing motion as hidden units after learning a latent manifold of human motions with a convolutional autoencoder. The hidden units are then mapped to high level control parameters by a feedforward neural network to generate motion on a given trajectory or curve of the terrain. Recurrent neural network have been also widely used for animation synthesis (Zhou et al. 2018), in particular phase function neural network has been applied by Holden et al. (2017) to synthesize human walk animations. Gaisbauer et al. (2019) proposed a fully-connected feed-forward neural network to blend between a start and end posture to generate walking animations. Similarly to blending-based and statistical-based approaches, the main drawback of deep-learning based motion synthesis is that the generated motions are part of the input database distribution and struggle to generate motions with characteristics “outside” the ones of the input database. Furthermore, few methods offer controls on high level parameters relevant for animators such as walking speed or step length which restrains the ability to generate and edit

motions with precise characteristics.

### 2.2.3 Physics-based

Enabling characters not only to move but also to interact with their surrounding is difficult using only example-based methods, as it requires to have an example motion for each type of scenario that the virtual characters will encounter. Physics-based approaches rely instead on mechanical laws to compute accelerations from forces and angular positions from torques. This additional dynamic information enables virtual characters to respond to external perturbations, such as someone pushing them, which is more difficult to naturally control with only kinematic information. Early works from Armstrong and Green (1985) laid the main foundations of driving motion of a virtual character using physics simulation. First they constructed a *character model* as a set of segments (or links) and joints, then they formulated the equations of motion for each segment in terms of a moving frame attached to the proximal joint of the segment. The different equations of motion provide the effect of torques, forces and acceleration of a segment at the parent and child joint. By solving the equations at different time steps, it is possible to generate the *character model* motion. In particular forward dynamics will provide segment and joint motions (accelerations, velocities, positions and orientations of the segments through time) given the torques and external forces, while inverse dynamics is generating character model motion by solving the equations in the inverse way (torques given accelerations, velocities and positions). Finally to make a *character model* perform its goal task, *motion controllers* are key to generate actuation patterns that drive the motion, which Geijtenbeek and Pronost (2012) define as a virtual brain. Thus to generate motions from physics, three key components are required. A *simulator* which will solve the equation of motion in real time, a *character model* that will act on the simulation and a *motion controller* to control it (Geijtenbeek and Pronost 2012). Research in physics-based simulations focused on improving the *character model* and *motion controller* to improve the quality of synthesized walking animations. More recently, Deep Learning approaches have also been explored to improve physics-based simulations (Peng et al. 2018).

#### Character Model

To generate bipedal walking motions, most physics-based characters are modelled according to humans. However due to the high complexity of the human musculoskeletal

system, the characters are always simplified versions of humans. One of the most common representation of biped characters consists in a simple set of segments and joints (Armstrong and Green 1985). Segments possess their mass information, necessary to solve the dynamic equation of motions, and are often modeled as simple geometry forms such as spheres, cylinders or boxes. These segments are connected through joints constrained by joint limits to better model a human joint. Such models of segment and joints have been widely used to produce simple but efficient bipedal locomotion (Yin et al. 2007). To enhance generated motions, other studies adapted the character model to their control strategy (Collins et al. 2005) or add segments at specific body parts (Wang et al. 2012). The forces and torques producing joint and segment motions need to be realistic to generate more human-like motions. To do so, the mechanisms generating the forces and torques (actuators) are implemented within the characters. This can be performed by adding mechanisms mimicking muscle contraction (Geyer and Herr 2010; Geijtenbeek et al. 2013; Lee et al. 2019) using real human musculotendon measurements (Rajagopal et al. 2016).

### **Motion Controller**

Now that the character model possesses segments joints and actuators, they still require a purpose to activate their actuators and move their body. *Motion controllers* aims at activating the mechanisms driving the motion. The interaction between the character and controller is possible through high-level control parameters (walking speed for example). Geijtenbeek and Pronost (2012) present an extensive list of motion controllers and regroup them in three categories: joint-space motion control, stimulus-response network control and constrained dynamics optimization control, each one having their own strength and weaknesses. The first category enables characters to move and adapt to different terrains (Yin et al. 2007) or tasks (Coros et al. 2010) but suffer a lack of coordination as each joint is controlled individually and independently. The second category of controllers provided early success (Coros et al. 2008; Yin et al. 2008) but present a more complex design to be fully efficient. The latter category provides overall better results than the two first categories, enabling bipedal creatures to walk by using balance (Geijtenbeek et al. 2013), or end-effector position (De Lasa et al. 2010) as control parameters.

Physics-based simulation is an interesting alternative for generating human walking motions. Using dynamics to drive motions in combination with constraints enables such methods to generate motions that respect the natural joint angles that humans usually

perform and allows the virtual character to adapt to perturbations in its environment. However, they require extensive offline computations to be generated which reduces the possibility to quickly populate large crowds efficiently. Furthermore, these methods often produce robot like motions and are rarely perceptually validated by observers which is critical in computer graphics as observers are humans used to easily recognize biological motions.

## 2.3 Perception of human motion

In this section we first present works that deal with the perception of biological motion, to understand what are the main features dictating the perception of walking. We then present studies that investigated how walking motion is perceived in the context of computer animation.

### 2.3.1 Perception of biological human motion

Perception of biological motion has been an active field of research since pioneer works from Johansson (1973). He demonstrated that a few bright spots positioned on a person's body, and placed over a contrasted background, were enough to be perceived as a human motion (see Figure 2.5). This Point Light Display (PLD) representation of human motion opened a wide range of questioning on the perception of biological motion by enabling researchers to remove any size and shape cues and focus solely on motion. Psychological studies used this framework to perform experiments in which they demonstrated that PLD enabled to perceive several anthropomorphic features. In particular, it has been showed that observers could discriminate the gender of a walker using PLD stimuli (Kozlowski and Cutting 1977; Mather and Murdoch 1994). Barclay et al. (1978) studied more in depth the spatial and temporal factors of gait pattern affecting gender perception and found that 2 step cycles (depending on walking speed) were sufficient to recognize gender. They also argue that hip and shoulder are the most important joints for gender recognition, enabling Cutting (1978) to synthesize point light walkers with specific gender information. Troje built on these results to design a framework classifying gender from motion (Troje 2002). Other features have been found to be recognizable from motion. In particular emotions were recognized from a PLD waker (Atkinson et al. 2004; Halovic and Kroos 2018), with anger being more easily perceived than happiness, sadness, fear or emotionless motion

(Chouchourelou et al. 2006). Cutting and Kozlowski also demonstrated that observers were able to recognize a specific friend pattern when familiarity cues were removed using PLD (1977), while Loula et al. (2005) demonstrated that observers were better in recognizing their own motion, followed by their friends' motion followed by strangers' motion. The main objective of using a PLD representation is to remove any static cue that could affect the perception of biological motion. However, it also has been shown that observers are able to estimate such static cues, relying solely on motion, such as the size of a walking creature (Jokisch and Troje 2003).

In the context of the perception of motion invariants, some researchers have also demonstrated that human visual perception is sensitive to such invariant laws. In particular, early works from Cutting et al. (1978) proposed the Center of Moment as a biomechanical invariant used by observers to discriminate between male and female walkers. Other studies focused on the perception of laws of motions. For instance, Dayan et al. (2007) demonstrated that human visual perception is influenced by stimuli complying with the two-thirds power law, an invariant of human hand motion. Moreover, Polyakov et al. (2009) suggested to use parabolic motion primitives as a control principle for arm movement, as they both respect the two-thirds power law and minimize jerk.

In the context of psychology, the perception of biological motion has thus been mainly studied using PLDs to remove any static cue and investigate how features are perceived solely based on the presence of motions cues. However, in the context of computer graphics, such static cues are available to the observer's eye. In particular, the walking character displayed on screen is usually in an environment composed of other characters and objects that provide additional size information to the observers. It also possess a model with a specific texture and clothes providing specific gender, age or weight information to the observers. Furthermore, many of the studies investigating the perception of biological motion used a side view providing only 2D information to the observer, even though some studies proposed to evaluate different viewpoints (Jokisch et al. 2006). However virtual humans are 3D characters, which provide additional cues to the observers. Thus, virtual humans convey more information than PLD when animated with a walking motion (Chaminade et al. 2007) and some researchers focus on investigating the perception of biological motion when applied on virtual characters.



Figure 2.5: Typical point light display stimuli representation of a human walking, adapted from Kern et al. (2013)

### 2.3.2 Perception in the context of Computer Animation

Studies in the Computer Graphics field are striving to access the perception of motion to improve realism of virtual characters' motions. In this context, perception of biological human motion is more often assessed displayed on 3D characters which convey more information than PLD (Chaminade et al. 2007). Thus, some features perceived by viewers using PLD were also perceived by viewers when motions are displayed on virtual characters. In particular, McDonnell et al. (2009) showed that the perception of the sex of virtual characters is influenced by both their form and their motion. They used 4 character representations: PLD, an androgynous character and both female and male characters on which they applied 3 different walking animations: female motion capture, male motion capture and neutral synthetic. They found that for neutral synthetic motions, form was the main factor influencing the perception of sex, while captured motions determine the perceived sex for the androgynous and male and female characters.

McDonnell et al. (2009) also investigated the perception of emotions by applying captured walking motions depicting various emotions on different virtual characters representation, including PLD and realistic 3D characters. They found that emotion were rated less intense when using a PLD representation than a virtual character, suggesting that motion was more important than form for the perception of emotions. Zibrek et al. (2015) extended these studies by demonstrating that the perception of gender was influenced by

walking motion conveying emotions and that, similarly to PLD, anger has more impact on the perception of gender.

As explained in the previous section, animating walking virtual characters is often performed by applying a limited number of motion capture data. If the required number of characters is higher than the number of available motions, some characters will share the same motion, leading to *motion clones*. Thus, different studies investigated the perception of *motion clones* and motion variety to control for the quantity of required animations. In particular McDonnell et al. (2008) explored the effect of crowd variety both in terms of appearance and motion. They showed that *motion clones* are significantly more difficult to spot than *appearance clones*, which can be masked by color variation, random orientation, and motion. They also found that the higher the number of *motion clones*, the easier observers notice them. Pražák and O’Sullivan (2011), in scenarios involving 8 to 24 characters with a generic appearance, demonstrated that cloning 3 unique motions was sufficient to create virtual crowds that were perceived as varied as when using a unique motion for each character. Hoyet et al. (2013) showed that the motions of some actors can be more distinctive than others, which may affect the perception of motion clones if a small number of distinctive motions are selected to animate a large number of characters. Thus, special care is required when selecting motions for animating virtual characters to obtain an environment with varied animated characters.

While the previous studies provided insights on the quantity of motions required to enhance motion variety, it is also important to consider the quality of the animations to maximize their efficiency. In particular, to avoid *motion clones* to be spotted by viewers, one can synthesize new animations, using techniques described in Section 2.2 for example. However, the synthesized motion need to be controlled in terms of quality to generate appealing crowd scenarios while preserving low resources costs. Indeed, editing motions without control can lead to animations that are easily detectable by observers. For instance, Prażak et al. (2010) demonstrated that observers perceived more easily artifacts in motions than are speeded up than motions that are slowed down. Safanova and Hodgins (2005) provided guidelines to produce more natural looking motions by evaluating the physical correctness of interpolated motions mathematically, while Wang and Bodenheimer (2008) proposed a perceptual study to develop methods for computing visually appealing blended motions. The quality can also be selected depending on where participants are expected to attend to (e.g. foreground) using level of details approaches (Kulpa et al. 2011).

Finally, is it also important to understand where to add variation as some body parts are more attended to by observers than others when trying to detect *appearance clones* and *motion clones* (McDonnell et al. 2009c). In particular, the head and upper torso are the most observed segments in such tasks, motivating Hoyet et al. (2016) to add shoulder motions to enhance the visual quality of crowd scenarios.

## 2.4 Conclusion

In this chapter, we first presented how walking was studied from a biomechanical point of view, then explained how researchers try to replicate walking motions for computer graphics applications. We demonstrated that walking motions can be synthesized with various techniques, each of them presenting advantages and disadvantages. Such animations are destined for computer animations where walking characters are required. However, as we demonstrated in the last section of this chapter, humans are efficient in recognizing features from motions which require the synthesized animations to be evaluated on their realism. To improve this realism, we propose in this thesis to use biomechanical parameters of human motion to synthesize and control walking animations adapted to specific characters' characteristics which are then evaluated through perceptual studies.

# WALK RATIO: PERCEPTION OF A BIOMECHANICAL PARAMETER OF HUMAN WALKING

---

## Contents

---

<b>3.1</b>	<b>Methods . . . . .</b>	<b>45</b>
3.1.1	Stimuli Preparation . . . . .	45
3.1.2	Blend Tree . . . . .	46
<b>3.2</b>	<b>Perceptual experiment . . . . .</b>	<b>48</b>
3.2.1	Participants . . . . .	48
3.2.2	Task . . . . .	48
3.2.3	Experimental Design . . . . .	49
3.2.4	Analysis . . . . .	49
<b>3.3</b>	<b>Results . . . . .</b>	<b>50</b>
<b>3.4</b>	<b>Discussion . . . . .</b>	<b>53</b>
3.4.1	Perception of the Walk Ratio . . . . .	53
3.4.2	Limitations . . . . .	55

---

In this chapter, we present the first scientific contribution of this thesis. From the analysis of the literature in Chapter 2, little is known about the perception of biomechanical parameters of walking motions when displayed on virtual characters and specially their effect on the perceived realism. However, understanding the perception of these parameters is valuable for the computer graphics community, as it would give a better understanding of what makes a motion look natural to observers and help in more accurate designing of virtual human motions. Furthermore, knowing how walking motions are perceived according to a range of actors' characteristics would provide further insights on how to generate and modify them so that they are adapted to a virtual character with specific

characteristics, e.g. to better design crowds with various characters.

Among the different biomechanical parameters of human walking, we decided to investigate the Walk Ratio. As presented in Chapter 2, the Walk Ratio is defined as the ratio of step length and step frequency freely chosen by a person when walking at comfort speed. This ratio was shown to be invariant at different walking speeds (Sekiya et al. 1997) for a given individual, while being influenced by gender, age and height (Murray et al. 1966; Hollman et al. 2011). These properties look promising for a potential use of this Ratio as a control parameter for virtual character walking animations. These properties would enable us to easily manipulate high level parameters such as step length and step frequency through the Walk Ratio, to automatically generate and modify motions and adapt them to virtual humans with specific characteristics, e.g. gender, height or speed. The general aim of this chapter is therefore to investigate whether the Walk Ratio can be an interesting variable to control when animating virtual characters, for instance to generate realistic variability in virtual human animations of locomotion movements.

More specifically, in this chapter we explore the ability of viewers to determine how different combinations of step length and step frequency are perceived when animating walking virtual characters. Our goal is therefore to investigate the ability of viewers to identify the Walk Ratio of specific actors when their motions are applied on virtual characters. To explore this issue, we conducted a perceptual experiment in which participants were asked to adjust the motions of virtual characters animated with motion capture data of 4 different actors walking at various step length and step frequency combinations. Walking speed was kept constant in each trial while participants adjusted the step frequency, leading to virtual characters walking with motions on a continuum from short steps with high step frequency, to long steps with low step frequency, therefore displaying a range of Walk Ratios. The contributions of this study are the following:

- We demonstrated the ability of observers to rate natural walk ratios as within the range of Walk Ratios observed in the literature.
- We demonstrated that the main characteristics of the Walk Ratio presented in the biomechanical literature were perceived by observers.

The remaining of the chapter is organized as follows. Section 3.1 presents the creation of the stimuli of our study, Section 3.2 presents the details and stimuli of the perceptual experiment, while Section 3.3 presents the results which are discussed in Section 3.4.

## 3.1 Methods

We designed an experiment to evaluate the ability of observers to evaluate the Walk Ratio of actors when their motion is applied to virtual characters. As it has been demonstrated in the literature, the Walk Ratio presents differences according to the sex of the walker (Sekiya et al. 1996; Cho et al. 2004). In particular, we expected that viewers would estimate a lower Walk Ratio for female than male actors as female tend to walk with shorter steps and higher step frequencies than male (Frimenko et al. 2014). We also expected viewers to estimate a similar Walk Ratio value for an actor walking at different speeds, as it was demonstrated to be invariant at different freely chosen walking speeds (Sekiya et al. 1997; Sekiya and Nagasaki 1998). Thus, our main hypotheses are:

- **H1.** The Walk Ratio of motions displayed on virtual characters, as chosen by viewers as being the most natural, will be lower for female than for male actors.
- **H2.** The Walk Ratio of motions displayed on virtual characters, as chosen by viewers as being the most natural, will be invariant according to the walking speed.
- **H3.** Viewers will be able to recognize the natural Walk Ratio for each individual actor when applied to his/her virtual counterpart.

### 3.1.1 Stimuli Preparation

For the purpose of the experiment, we captured the locomotion of 4 actors (2 males, 2 females) with no disability or neurological disorder that could affect their locomotion. Their height and age were respectively: F1 (1.78m, 26 years old), F2 (1.68m, 36 years old), M1 (1.80m, 25 years old), M2 (1.78m, 20 years old). Motion capture was conducted using a Xsens IMU-based motion capture system at a sampling rate of 120 Hz (see Figure 3.1). We asked each actor to perform 15-meter straight walks according to different conditions. First, they were asked to walk at 5 different self-selected speeds (very slow, slow, comfort, fast and very fast) summarised in Table 3.1. They always started with the comfort walking speed and could train as long as they wished for each speed before being recorded. No additional constraint was given, leaving the choice of step length and step frequency to the actors. We then recorded a series of locomotion while varying step length and step frequency. Actors were instructed to adapt their step frequency to the sound of a metronome set from 80 steps per min (spm) to 120spm with a 10spm increase. For each frequency, we asked them to vary the length of their steps as following: very small, small,

Table 3.1: Summary of the walking speeds achieved by our four actors

		Actor			
		F1	F2	M1	M2
Speeds (m/s)	Very Slow	0.78	0.43	0.54	0.37
	Slow	1.11	0.73	0.89	1.06
	Comfort	1.24	1.06	1.48	1.35
	Fast	1.55	1.23	1.95	1.70
	Very Fast	2.07	1.90	2.45	2.00



Figure 3.1: Xsens Motion Capture system used to record the motion of our actors. The system consists in 17 IMU based sensors (right) placed within a motion capture suit (left). Each sensor is composed of accelerometers and gyroscopes. Figure taken from <http://www.xsens.com>.

comfort, long and very long steps, resulting in 25 imposed walks at different step length and step frequency combinations.

For each of the 25 combinations we then created 1-cycle looping animations, using an approach similar to that described by Kovar et al. (2002) and used by Hoyet et al. (2013). In short, the approach automatically identifies from the original data the two most similar frames separated by a locomotion cycle, and linearly blends the difference between these two frames over the sequence, before removing any residual footsliding using the method of Kovar et al.(2002).

### 3.1.2 Blend Tree

To control the walking animations, we designed a blend tree in Unity for each motion captured actor. A blend tree enables to smoothly blend motions by incorporating them to varying degrees. The amount that each of the motions contributes to the final effect

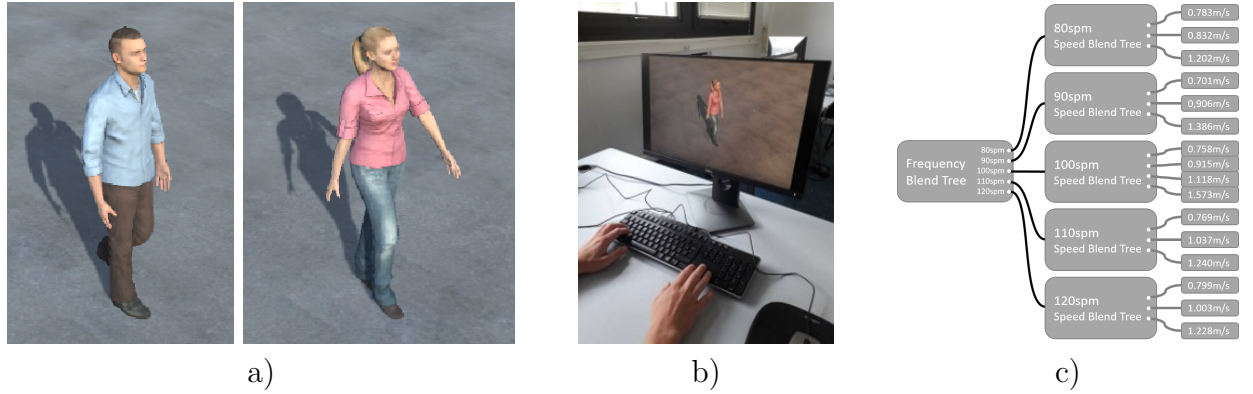


Figure 3.2: a) Male and female virtual character models used in our perceptual experiment. b) Perceptual experiment set up. c) Example of blend tree for the actor F2, used to output a motion at a specific speed and step frequency (spm: steps per min)

is controlled using a blending parameter. We designed the blend trees using the following procedure. After verifying that each 1-cycle walking motion was at the exact recorded step frequency, the motions of each actor were grouped according to their respective step frequency (i.e., 80, 90, 100, 110 or 120spm) in 5 different sub-blend trees. Within each sub-blend tree, each motion was identified by its exact walking speed, and we used the desired walking speed as the blend parameter to interpolate between motions in the blend tree. Each sub-blend tree also included enough motions so that we could accurately generate motions with walking speeds in the range of 0.8 to 1.2m/s. These 5 sub-blend trees were then controlled by a main blend tree which used the step frequency as a parameter to interpolate between the resulting motions (with the same speed) at different step frequencies. For instance, to obtain a walking animation at 1.0m/s and 85spm, the 80 and 90spm sub-blend trees would interpolate two of their respective walking motions to output a walking motion at 1.0m/s each, which would then be interpolated by the main blend tree to generate a walking animation with the desired step frequency and speed. Figure 3.2 depicts as example the blend tree of one of the female actors. The blend trees were associated to 4 different virtual characters using 1 female and 1 male model (see Figure 3.2), which height were scaled according to each corresponding motion captured actor. Each interpolated motion of each actor was checked for speed, as reported in Table 3.2.

Table 3.2: Interpolated speeds (mean $\pm$ SD) from the blend trees at the different expected step frequencies and speeds, averaged over all four actors' motions.

		Expected Speed (m/s)		
		0.80	1.00	1.20
<b>Step Frequency</b> (spm)	<b>80</b>	0.801 $\pm$ 0.006	0.997 $\pm$ 0.002	1.198 $\pm$ 0.002
	<b>90</b>	0.798 $\pm$ 0.001	0.996 $\pm$ 0.004	1.198 $\pm$ 0.004
	<b>100</b>	0.792 $\pm$ 0.006	0.993 $\pm$ 0.012	1.192 $\pm$ 0.008
	<b>110</b>	0.798 $\pm$ 0.002	1.000 $\pm$ 0.002	1.199 $\pm$ 0.005
	<b>120</b>	0.816 $\pm$ 0.027	1.000 $\pm$ 0.008	1.203 $\pm$ 0.006

## 3.2 Perceptual experiment

### 3.2.1 Participants

Twenty-two participants (10F and 12M, age: mean=27.6 $\pm$ 6.2, min=20, max=47) were recruited for the perceptual experiment. All participants volunteered for the experiment, and were recruited using internal mailing lists. Participants did not receive any compensation. They were all naive to the purpose of the experiment, and gave written and informed consent. The study conformed to the declaration of Helsinki. During the experience, they could ask for a break at any moment. At the end of the experience, a feedback was given on the objectives and the purpose of the experiment.

### 3.2.2 Task

Participants were instructed to modify the step frequency of the virtual characters. As walking speed of the character was kept constant, changing the step frequency therefore led the blend tree to automatically produce the adequate combination of step frequency and step length for the corresponding speed and therefore to indirectly change the Walk Ratio. We thus asked participants to modify continuously the step frequency of the virtual character presented on a 24-inch screen by pressing and holding the left and right arrow keys on a keyboard, until they found the motion to be most natural in their opinion. No information was given on what was a natural motion, but they were instructed that one key increased step frequency, while the other decreased it. Participants were also first presented with two training stimuli which motions were not from the actors used in the experiment, depicting successively a high step frequency motion and a low step frequency motion, both at the same speed.

### 3.2.3 Experimental Design

Participants were presented with virtual characters displaying the movements of the 4 actors, and walking at 3 different walking speeds (0.8, 1.0 and 1.2m/s), using the blend trees described in Section 3.1.2. For each Actor  $\times$  Speed combination, step frequencies were initialized once at a maximum of 120spm, and once at a minimum of 80spm to avoid any effect of the initialisation value of the stimuli. Thus for half of the trials, the virtual walker appeared on screen with an initial step frequency of 80spm and for the other half, the character appeared on the screen with an initial step frequency of 120spm. In total 96 stimuli were presented in a random order to the participants: 4 Actors  $\times$  3 Speeds  $\times$  2 Initialization  $\times$  4 Repetitions. All the stimuli were displayed with the character walking in the middle of the screen using a typical canonical viewpoint (Figure 3.2), which is a viewpoint commonly used in video games and providing as much information as possible about the studied motions.

### 3.2.4 Analysis

From the perceptual study, as participants' answers corresponded to the motion they considered to be the most natural (i.e., a certain combination of step length and step frequency for a given speed), we computed the corresponding Walk Ratio perceived as the most natural by the observers. Statistical analysis was performed using the Jamovi software. Significant level was set at the 95% level, (i.e.,  $p < 0.05$ ). Normality was assessed using Shapiro-Wilk test.

To assess whether the experimental factors affected how participants perceive the Walk Ratio, we first performed a 4-way mixed repeated measure ANOVA with within-subject factors *Actor*, *Speed* and *Initialization*, and between-subject factor *Participant Sex*. Greenhouse-Geisser adjustments to the degrees of freedom were applied when appropriate to avoid any violation of the sphericity assumption. The Effect size is reported using partial eta squared ( $\eta_p^2$ ). A priori power analysis ( $\beta$ ) was performed from effect size, sample size and significance values using G\*Power software. When needed, Tukey post-hoc tests were performed for pairwise comparisons. To evaluate the accuracy of participants to recognize each actor's Walk Ratio, we also performed a one sample Student t-test for each actor, comparing his/her Walk Ratio as estimated by participants on the corresponding character with his/her Walk Ratio computed from the walking motion captured at comfort speed (see Section 3.1.1).

Table 3.3: ANOVA results of the perceptual experiment. Our factors are Actors, Speed, Initialisation (Init.) and Participant Sex (P. Sex). Significant results are displayed in bold, or identified with a † when post-hoc analysis did not confirm the significance of the effect.

Factor	F	p-value	$\eta_p^2$
<b>Actor</b>	<b>51.368</b>	<b>&lt;0.001</b>	<b>0.72</b>
Speed	1.729	0.19	0.08
Init.	0.512	0.483	0.025
P. Sex	0.117	0.736	0.006
<b>Actor x Speed</b>	<b>8.349</b>	<b>&lt;0.001</b>	<b>0.295</b>
Actor x Init	12.715	<0.001†	0.389
<b>Actor x P. Sex</b>	<b>2.846</b>	<b>0.045</b>	<b>0.125</b>
Speed x Init	6.706	0.003†	0.251
Speed x P. Sex	2.392	0.104	0.107
Init x P. Sex	1.619	0.218	0.075
Actor x Speed x Init	0.695	0.654	0.034
Actor x Speed x P. Sex	1.883	0.089	0.086
Actor x Init x P. Sex	1.27	0.293	0.06
Speed x Init x P. Sex	3.364	0.045†	0.144
Actor x Speed x Init x P. Sex	1.012	0.421	0.048

### 3.3 Results

Table 3.3 summarizes the effect of the experimental factors on the perceived Walk Ratio. The perceived Walk Ratio was highly affected by the Actor observed ( $p < 0.001$ ,  $\eta_p^2 = 0.720$ ,  $\beta = 0.99$ ), where post-hoc analysis showed that on average *the estimated Walk Ratio was significantly lower for female than male actors* ( $p < 0.001$ , see Figure 3.3). No difference was found between actors of the same sex. While we did not find an effect of Participant Sex ( $p = 0.736$ ) on the perceived Walk Ratio, we found a moderate interaction effect between Actor and Participant Sex ( $p = 0.003$ ,  $\eta_p^2 = 0.275$ ). Post-hoc analysis showed that Female 1 was perceived as significantly different from Male 1 and Male 2 whatever the sex of the participant, while Female 2 was perceived as significantly different from Male 1 and Male 2 only by male participants, but not by female participants (see Figure 3.4). This result therefore validates **H1**, while suggesting potential differences in the way male and female participants perceive natural Walk Ratios, which is discussed in Section 3.4.

Regarding walking speed, we did not find an effect of Speed on the perceived Walk

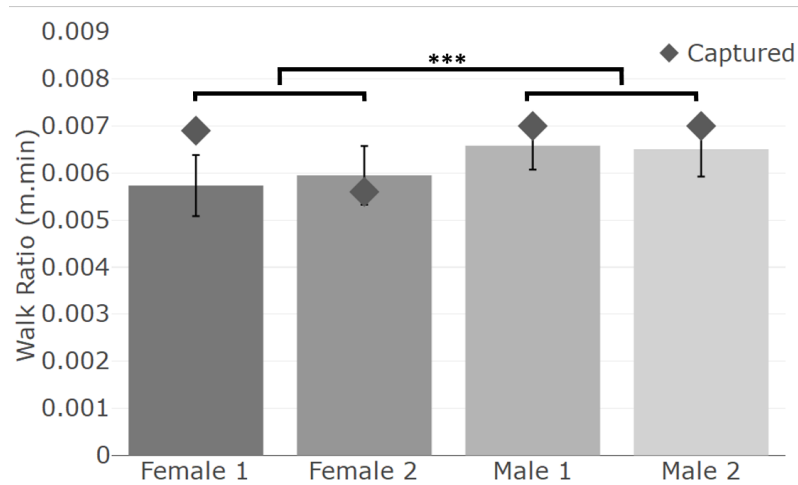


Figure 3.3: (Left) Main effect of Actor on the perceived Walk Ratio: the perceived Walk Ratio was significantly lower for female than male actors. The perceived Walk Ratios were estimated smaller than the captured Walk Ratio, depicted as red diamond, except for Female 2.

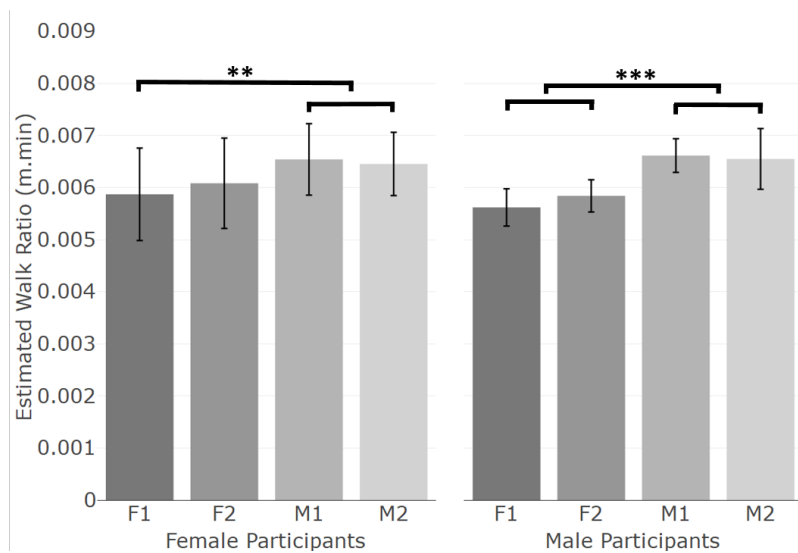


Figure 3.4: Interaction effect between Actor and Participant Sex on the estimated Walk Ratio. Post-hoc analysis showed that Female 1 was perceived as significantly different from Male 1 and Male 2 whatever the sex of the participant, while Female 2 was perceived as significantly different from Male 1 and Male 2 only by male participants, but not by female participants.

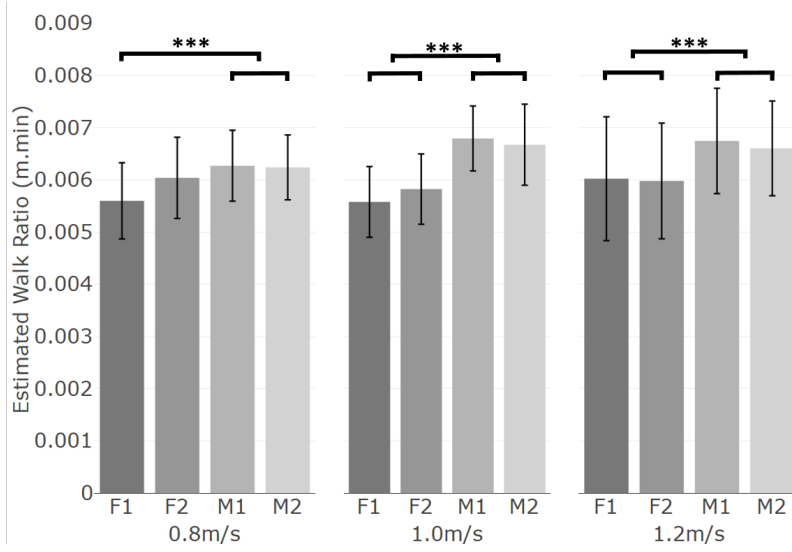


Figure 3.5: Interaction effect between Actor and Speed on the estimated Walk Ratio. The perceived Walk Ratios were significantly different at 1.0 and 1.2 m/s between Female and Male actors. At 0.8 m/s, only the Walk Ratio of Female 1 was statistically different from the Male actors. For a given actor, there was no difference in the perceived Walk Ratio across speeds.

Ratio ( $p = 0.190$ ). This result supports **H2**, and is in agreement with the biomechanical literature where the measured Walk Ratio was found to be invariant at different freely chosen walking speeds (Sekiya et al. 1997; Sekiya and Nagasaki 1998). However, a moderate interaction effect between Actor and Speed was observed ( $p < 0.001$ ,  $\eta_p^2 = 0.295$ ,  $\beta = 0.99$ ), where post-hoc analysis showed that the Walk Ratio of both female actors were perceived to be significantly lower than the Walk Ratios of both male actors for 1.0m/s and 1.2m/s speeds, but that only the Walk Ratio of Female 1 was perceived to be significantly lower than those of male actors for the speed of 0.8m/s. In contrary, at 0.8m/s, the Walk Ratio of Female 2 was not perceived to be significantly different from male actors, but perceived to be significantly different from Female 1 (see Figure 3.5). There was however no effect of Initialisation ( $p = 0.483$ ) on the perceived Walk Ratio, which suggests that participants perceived similar natural Walk Ratio independently of the initial step frequency of the motion displayed.

Finally, when comparing the perceived and captured Walk Ratio for each actor (where the perceived walk ratio of each actor was averaged over Speed for each participant, as we did not find a significant effect of Speed), results showed significant differences reported in Table 3.4. All the estimated Walk Ratios were smaller than the motion captured ones,

Table 3.4: Motion captured and perceived Walk Ratios (m.min), with results of the one-sample student t-test comparing measured and perceived Walk ratios for each actor.

Actor	Female 1	Female 2	Male 1	Male 2
Captured	0.00690	0.00560	0.00700	0.00700
Estimated	0.00573	0.00595	0.00658	0.00651
SD	0.00065	0.00062	0.00051	0.00058
p-value	<b>&lt;0.001</b>	0.015	<b>&lt;0.001</b>	<b>&lt;0.001</b>

except for Female 2, which was perceived to be higher (see Figure 3.3, Left). This result therefore invalidates **H3**, and suggests that viewers might not be able to recognize the actual natural Walk Ratio of an individual when applied to a virtual character, even though perceived Walk Ratios were in the range of those measured in the literature and relative differences between actors were indeed perceived.

## 3.4 Discussion

In this chapter, we presented a perceptual experiment evaluating whether viewers are able to identify the natural Walk Ratio specific to an individual, when captured motions are displayed on a virtual character.

### 3.4.1 Perception of the Walk Ratio

First, results show that the natural Walk Ratio of the female actors was perceived to be significantly lower than the one of the male actors by the participants, which validates our hypothesis **H1**. This is the first time that this result, similar to what has been reported in the Movement Science literature about Walk Ratios measured on individuals actually walking (Sekiya et al. 1996; Cho et al. 2004), has been explored in relation to the perception of Walk Ratios. Furthermore, we found a slight difference in male and female participants' perceptions of the Walk Ratios regarding one female actor, where the perceived Walk Ratio of our Female 2 actor was not perceived to be significantly different from the Walk Ratios of male actors by female participants. While gender differences have been reported in the literature in the actual measurement of the Walk Ratio, there might also be gender differences in the way we perceive a natural Walk Ratio when animating

virtual characters. As this is the first attempt in evaluating the perception of this invariant parameter of human walking, it seems however difficult to explain the reason of the observed difference, especially given the small number of actors used for the experiment.

Second, similarly to the literature which showed that measured Walk Ratios are relatively invariant at different freely chosen walking speeds (in the range of 0.6 to 2.2m/s) (Sekiya et al. 1996; Murakami and Otaka 2017), we found that perceived Walk Ratios do not seem to be influenced by the speed of the virtual character’s motions, which validates our hypothesis **H2**. Our results however suggest that slight potential differences might still be perceived by viewers, as we found that the Walk Ratio of our Female 2 actor was perceived at a speed of 0.8m/s to be more similar to the Walk Ratio of our male actors than to the one of the other female actor.

Prior to the experiment, we also recorded our four actors walking at five different self-selected speeds, and measured their Walk Ratio from their self-selected step length and step frequency for each speed. The Walk Ratios we measured were in the range of those measured in the literature (Zarrugh et al. 1974; Sekiya et al. 1997) (see Figure 3.6). It is also interesting to point out that the Walk Ratios perceived as natural by the participants were in general lower than the motion captured Walk Ratios, except for Female 2, while also being in the same range than measured Walk Ratios found in the literature. This partially invalidates our hypothesis **H3**.

It is also important to mention that the Walk Ratio has been studied in the Movement Science literature both in absolute (Sekiya and Nagasaki 1998; Menz et al. 2003; Borel et al. 2004) and normalized (Sekiya et al. 1996; Nagasaki et al. 1996; Cho et al. 2004) manners, where normalization is usually either performed based on the person’s height or leg length to account for gender and height differences (Hof 1996). When normalized, Walk Ratios tend to present less gender differences than Walk Ratios studied in absolute values, indicating that morphology might be more prevalent in the differences in Walk Ratios. However, for a first study exploring the ability of observers to identify natural Walk Ratio, we chose to analyze the data using absolute values only to possibly observe gender differences as measured on real persons (Cho et al. 2004). This also seemed more appropriate given the small number of actors in our study, and thus the narrow pool of actor’s morphology. Moreover, while the effects of weight and Body Mass Index on various kinematic parameters during free walking have been widely studied (Silva-Hamu et al. 2013; Lai et al. 2008) there is, to our knowledge, no study investigating the effects of such factors on the Walk Ratio specifically.

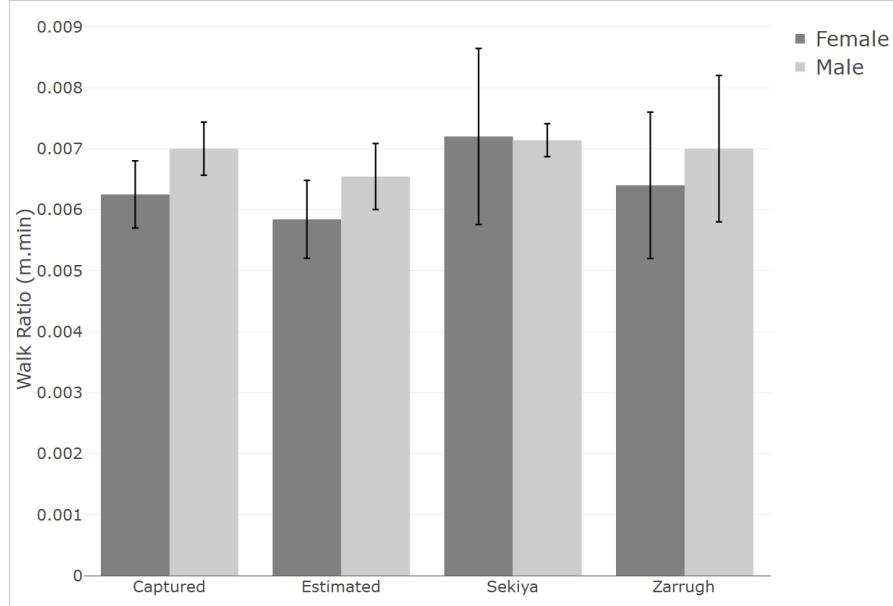


Figure 3.6: Estimated and motion captured Walk Ratios obtained in our study in comparison to previous works of Sekiya et al. (1997) and Zarrugh et al. (1974)

### 3.4.2 Limitations

A limitation of our study is that walking motions were limited to the 0.8m/s to 1.2m/s speed range, while the human natural walking speed generally ranges from 1.2 to 1.6m/s (Kerrigan et al. 2001). We purposely selected this range as we found in a pilot study that actors were able to comfortably follow the rhythm of the metronome when it was set between 80 and 120spm, resulting in a range of speeds from 0.57 to 1.6m/s. However, all the speeds were not obtained at all the step frequencies, which was required for completeness of the perceptual experiment. For example reaching 1.6m/s at 80spm would require actors to perform 1.3m long steps. We therefore decided to select a speed range enabling us to obtain speeds that both respected the physical capabilities of our actors, and the invariability of the Walk Ratio (Sekiya et al. 1996; Murakami and Otaka 2017). While the results in the range of speeds of our study indicate that participants perceived a similar Walk Ratio across speeds for a given actor, it would be interesting to further investigate the effect of higher walking speeds on the perception of the Walk Ratio. This would therefore also require to investigate these effects on a different range of step frequencies, more adapted to higher walking speeds.

One may also argue that we could have controlled step length over step frequency in the motion capture session. However, it has been demonstrated that controlling step

frequency shows less variability than controlling step length in human walk (Sekiya et al. 1997), hence our choice. Adjusting the motions of the virtual characters in the perceptual experiment raised the same questioning. We decided to let participants adjust the motion using the step frequency as Durgin et al. (2007) explained that step frequency dominates over step length in the perception of self motion in a treadmill VR experiment.

Similarly, viewpoint might have affected the results of the experiment. We displayed the stimuli using a typical canonical viewpoint, as done by Prazak et al. (2011) and Hoyet et al. (2016). In particular, this is a viewpoint typically used in the entertaining industry, especially in video-games. However, it would be interesting to find out if the results remain similar in other viewpoints that can be found in interactive applications.

Another potential limitation of our study is that we decided to use linear interpolation to generate the walking motions at the desired speed and step frequency (i.e., motion blending, a well know and widely used method in computer graphics) used as stimuli of our perceptual experiment. Studies demonstrated that averaged walking motions synthesized using linear interpolation were considered to be the most attractive when displayed amongst captured biological motions (Hoyet et al. 2013). Similarly, previous research explored the creation of visually appealing motion transitions using linear interpolation (Wang and Bodenheimer 2008a), or of physically correct interpolated motions (Safonova and Hodgins 2005; Reitsma and Pollard 2003). While it is a very popular method enabling to produce seamless and appealing motions when properly performed, little is however known about its effects on the perception of biological motion, and in the context of this study whether it might have an effect on the perception of Walk Ratios. It would therefore seem to be valuable for future studies to also investigate the consequences of synthesizing interpolated motions on motion perception.

Finally, when biological walking motions are applied to virtual characters, our results demonstrate that the Walk Ratio perceived by observers has the same characteristics than the Walk Ratio naturally selected by walkers in real conditions. We therefore believe that these results can provide new considerations to drive the animation of walking virtual characters using the Walk Ratio as a parameter, which is our next goal to explore. For instance, we would like to propose novel animations techniques to edit the speed of existing walking motions by modifying concurrently step frequency and step length, while preserving an individual’s characteristics by conserving the Walk Ratio of his/her original motion. It would also be interesting to explore how existing walking motions could be adapted to satisfy a novel Walk Ratio, so that the resulting motion would be perceived

as corresponding to an individual with different characteristics (e.g., an older character). While this is the first experiment exploring the perception of this invariant parameter of walking motions when displayed on virtual characters, and despite the fact that we found similarities between the perception of the Walk Ratio and actual measurements from the biomechanical literature, a last limitation our study is the small number of male and female actors considered. While we should ensure that the current results generalise to larger number of individuals, they could lever the creation of more realistic virtual character animations, such as for virtual crowds. Hence, in the following Chapter, we investigate in more details the effect of actors' characteristics (e.g., height, gender and weight) on the perceived Walk Ratio, exploring both absolute and normalized metrics when relevant. We also further investigate the differences we found between the motion captured and the perceived Walk Ratios. In particular we explore the use of Virtual Reality on the perception of the Walk Ratio, as a more immersive environment might improve perception of depth and height. As Virtual Reality studies often occur in specific conditions, e.g. self-motion from a first person perspective (Banton et al. 2005; Durgin et al. 2007), we adapt our framework to evaluate the perception of a motion of character to evaluate the misperceptions between captured and estimated Walk Ratios that we found in this Chapter.



# PERCEPTION OF THE WALK RATIO: GENERALISATION AND ANIMATION GUIDELINES

---

## Contents

---

<b>4.1</b>	<b>Methods . . . . .</b>	<b>61</b>
4.1.1	Stimuli Preparation . . . . .	62
4.1.2	Task . . . . .	62
4.1.3	Participants . . . . .	64
<b>4.2</b>	<b>Analysis . . . . .</b>	<b>64</b>
4.2.1	Collected Data . . . . .	64
4.2.2	Statistics . . . . .	66
<b>4.3</b>	<b>Results . . . . .</b>	<b>66</b>
4.3.1	Perception of the Walk Ratio . . . . .	66
4.3.2	Eye Tracking Data . . . . .	69
<b>4.4</b>	<b>Discussion . . . . .</b>	<b>71</b>
4.4.1	Perception of the Walk Ratio . . . . .	71
4.4.2	Guidelines for the control of virtual character walking animations	75

---

In the previous chapter, we demonstrated that the main characteristics of the Walk Ratio (gender difference and speed invariance) are perceived by observers. However, we also found that estimated Walk Ratios were statistically different from the corresponding natural Walk Ratio of the original actors in general. While these preliminary results suggest that the Walk Ratio could be a valuable parameter to control virtual character's motion in an individual specific manner, a number of questions still remain to explore in relation to its usage. First, the previous study focused solely on 4 actors as a first investigation of the perception of the Walk Ratio, which questions whether the results found

in this study would generalise to more actors. Second, the results of our first contribution indicate that there is a gender difference in the perception of the Walk Ratio. However, due to the low number of actors it is not entirely clear if this gender difference is an actual gender difference or a consequence of the morphological differences between our actors. We are also interested in investigating the impact of different viewing conditions on the perception of the Walk Ratio. In particular, we wonder if the motion is more important than the appearance of the virtual characters when estimating the Walk Ratio. We are also interested in investigating whether using Virtual Reality (VR) in a Head Mounted Display would have an effect on the perception of the Walk Ratio, as such a tool enables to display the virtual characters in 3D with its real height and might therefore be beneficial to identify the actual natural Walk Ratio of actors.

Thus, in this second scientific contribution, we further investigate these questions in relation to the perception of the Walk Ratio. To explore these issues, we conducted a perceptual experiment using the same paradigm as in the previous contribution with the following differences. We increased our actor pool to 16 individuals and used their comfort walking speed, as we showed in the previous contribution that the Walk Ratio was perceived to be invariant across speed for a given individual. We displayed the motions on two different character models, one matching actor's gender and one not matching it. Finally we presented the stimuli in a screen condition for half of the participants and in a VR condition for the other half.

In the context of virtual character animation, the contributions of this study are the following:

- We demonstrated that the perception of the Walk Ratio was influenced by both gender and individual speed when observed in absolute values, and by speed when normalized by participant's height.
- We demonstrated that these characteristics were perceived similarly across different display conditions.
- We found no difference between the perception of the Walk Ratio when the motion is applied on gender-matched and gender-mismatched virtual characters.
- We provide guidelines regarding the control of walking motions of virtual characters through the Walk Ratio.

The remaining of the chapter is organized as follows. Section 4.1 presents the creation of the stimuli of our study and details the methodology used to design the perceptual

experiment, while Section 4.2 and Section 4.3 present respectively the analyses and the results which are discussed in Section 4.4.

## 4.1 Methods

We designed a user study to evaluate the influence of different actor characteristics and display conditions on the perception of the Walk Ratio. We used a similar framework to the experiment presented in Chapter 3 with the following differences. We increased the actor pool to 16 actors (8F, 8M) depicting a varied range of height and weight. The motions were displayed on a virtual character whose gender matched the gender of the corresponding original actor as in Chapter 3, but also on a virtual character whose gender did not match the gender of the corresponding original actor. We also displayed the motions on two different setups, on a traditional screen as in Chapter 3 with a side viewpoint, and in a Virtual Reality condition using a Head Mounted Display and the same side viewpoint.

As for the previous study, we expected that viewers would estimate a lower Walk Ratio for female than male actors. We also expected that taller actors would be associated with higher Walk Ratios, as taller people tend to perform longer steps. Similarly, we expected that participants in the Head Mounted Display condition would perform better in estimating a Walk Ratio close to the natural Walk Ratio of the actors than participants in the screen condition. Finally, we expected that the Walk Ratio of a specific actor would remain similar when its motion is applied on a gender-matched or gender-mismatch model, i.e. that the Walk Ratio is driven more by the character’s kinematics than its appearance.

Thus, our main hypotheses are:

- **H1.** The Walk Ratio of motions displayed on virtual characters, as chosen by viewers as being the most natural, will be lower for female than for male actors.
- **H2.** The Walk Ratio of motions displayed on virtual characters, as chosen by viewers as being the most natural, will be higher for taller actors.
- **H3.** Viewers will evaluate the same Walk Ratio of a given actor when the motion is displayed on gender-matched or gender-mismatched character models.
- **H4.** Viewers will be able to more accurately recognize the natural Walk Ratio for each individual actor when applied to their virtual counterpart in the VR than the screen condition.

Table 4.1: Actors’ summary.

<b>Actor</b>	<b>F1</b>	<b>F2</b>	<b>F3</b>	<b>F4</b>	<b>F5</b>	<b>F6</b>	<b>F7</b>	<b>F8</b>	<b>mean</b>
Age (years)	26	36	23	24	25	28	23	32	27±4
Height (cm)	178	168	165	170	166	166.5	169	167	169±4
Weight (kg)	80	72	56	61	61	54	83	68	67±11
Comfort	1.07	1.20	1.35	1.01	1.00	1.22	1.11	1.25	1.15±0.12
Walking Speed(m/s)									
<b>Actor</b>	<b>M1</b>	<b>M2</b>	<b>M3</b>	<b>M4</b>	<b>M5</b>	<b>M6</b>	<b>M7</b>	<b>M8</b>	<b>mean</b>
Age (years)	25	20	25	28	24	23	23	32	26±3
Height (cm)	180	178	186	181	182	168	172	184	179±6
Weight (kg)	83	75	95	72	77	65	70	83	78±9
Comfort	1.31	1.15	0.98	1.10	0.97	1.06	1.29	1.15	1.12±0.12
Walking Speed(m/s)									

#### 4.1.1 Stimuli Preparation

For the purpose of the experiment, we captured the locomotion of 16 actors (8 females and 8 males), using the method previously described in Section 3.1.1. The age, height, weight and comfort walking speed of the 16 actors (including the four actors captured for the first experiment: F1, F2, M1, M2) are summarized in Table 4.1. Similarly, a blend tree was designed in Unity for each motion captured actor using the procedure described in Section 3.1.2.

#### 4.1.2 Task

For this experiment, we used the same task than in the first experiment, as presented in Section 3.2.2. Participants were however presented with virtual characters displaying the motions of 16 actors, and walking at the actor’s comfort speed. For each motion, step frequencies were initialized once at a maximum of 120spm, and once at a minimum of 80spm to avoid any effect of the initialisation value of the stimuli. For each actor we selected 1 Female and 1 Male virtual character to display the motion (see Figure 4.1), which height were scaled according to each corresponding motion captured actor. In the following, we will refer to gender-matched when the gender of the actor and gender of the virtual character are the same, and gender-mismatched when the gender of the actor and of the virtual character are different. In total 128 stimuli were presented in a random order to the participants: 16 Actors  $\times$  2 Character Gender (matched/mismatched)  $\times$  2 Initializations  $\times$  2 Repetitions. To accurately compare the two viewing conditions (screen and

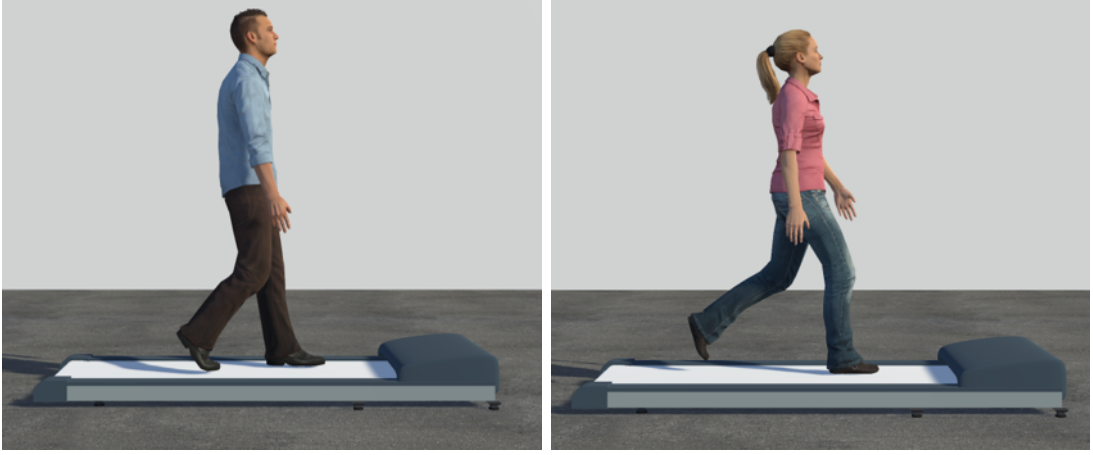


Figure 4.1: Side view used in the second experiment. The motions were displayed on a treadmill to keep a consistent viewpoint between Screen and Virtual Reality conditions.

VR), it was important to present the stimuli similarly across these two viewpoints. In the experiment presented in Chapter 3, the virtual camera used to display the virtual character was following the character which can be troublesome in a VR condition. In particular if the movement of the camera is different from the movement of the participant's head, motion sickness can occur. We thus decided to adapt a side view in both screen and VR conditions, as seen in Figure 4.1, by using a treadmill and applying all the motions on spot. This view was static in the screen condition but we allowed small parallax when participants moved their head in the HMD condition. Therefore, half of the participants performed the experiment using a 24-inch screen (60Hz frame rate), modifying the step frequency by pressing and holding the left and right arrow keys on a keyboard while the other half of the participants performed the experiment using a FOVE Virtual Reality Head Mounted Display (FOVE VR HMD, 70Hz, 90-100° field of view, Figure 4.2), modifying step frequency using the joystick of a Logitech F710 S gamepad, in a between subject experimental design. The camera eye height was fixed and similar for all the participant and no avatar was used to represent the participant.

As an eyetracker (120Hz) is integrated with the FOVE VR HMD, we also decided to record where participants were looking during the experiment to gain potentially additional insights about the usual strategies used to evaluate the natural Walk Ratio of characters.

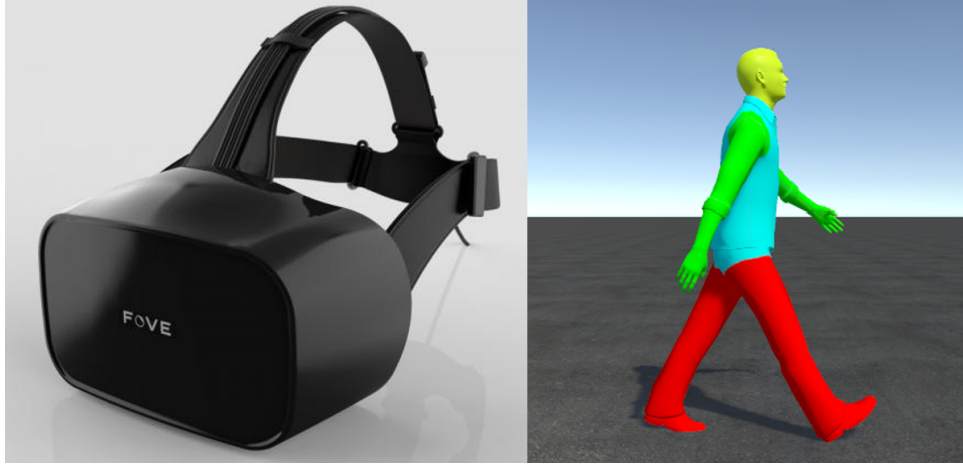


Figure 4.2: FOVE system used in our head mounted condition (Left) and material used for tracking the body parts most observed by the participants during the VR condition (Right).

### 4.1.3 Participants

A total of 28 participants (14 females and 14 males, age: mean= $26 \pm 3$ , min = 21, max = 33) were recruited for the experiment: 14 participants (7 females and 7 males) were presented with the Screen condition, and 14 different participants (7 females and 7 males) were presented with the Virtual Reality condition. All participants volunteered for the experiment, and were recruited using internal mailing lists. Participant did not receive any compensation. They were all naive to the purpose of the experiment, and gave written and informed consent. The study conformed to the declaration of Helsinki. During the experience, they could ask for a break at any moment. At the end of the experience, a feedback was given on the objectives and the purpose of the experiment.

## 4.2 Analysis

### 4.2.1 Collected Data

#### Perceived Walk Ratio

From the perceptual study, as participants' answers corresponded to the motion they considered to be the most natural (i.e., a certain combination of step length and step frequency for a given speed), we computed the corresponding Walk Ratio perceived as the most natural by the observers (i.e. when they pressed a specific key to validate their

choice) using a custom Unity script. We averaged the responses of the participants across the two repetitions. As we want to determine the effects of gender, weight, height and speed, we first collected and analysed the absolute values of the perceived Walk Ratios. We then proceeded to the analysis of the perceived Walk Ratio after normalisation. As the walking speed ( $v$ ) is fixed and step frequency ( $SF$ ) is known from the controller of the motion, we can compute the corresponding Walk Ratio ( $WR$ ) and step length ( $SL$ ). We then performed the normalisation using recommendations from Hof (1996) and Pinzone et al. (2016), with the height ( $H$ ) instead of the leg length of each actor:

$$SL_n = SL/H \quad (4.1)$$

$$SF_n = SF/\sqrt{g/H} \quad (4.2)$$

$$v_n = v/\sqrt{g.H} \quad (4.3)$$

$$WR_n = SL_n/SF_n \quad (4.4)$$

with  $SL_n$ ,  $SF_n$ ,  $v_n$  and  $WR_n$  the normalised step length, step frequency, walking speed and perceived Walk Ratio and  $g$  the acceleration of gravity on earth.

## Eye-Tracking Data

For the Virtual Reality condition, we also recorded the 2D position of the gaze of the participants at each frame of the experiment using the FOVE built-in eye-tracking system and the Unity FOVE plugin (see Figure 4.2). We designed a material in unity applied to the virtual characters in our experiment, but not visible by the participants. The material consisted in 4 different colors, (red for the legs, green for the hands, blue for the torso and yellow for the head) as seen in Figure 4.2. At each frame, we computed the 2D position of the gaze within the application and recorded the body part the participants were looking at, using a custom shader.

### 4.2.2 Statistics

Statistical analysis was performed using the Jamovi software. Significance level was set at the 95% level, (i.e.,  $p < 0.05$ ). Normality was assessed using Shapiro-Wilk test. As normality was respected, we performed two 4-way repeated measure Analysis of Variance (ANOVA) with within-subject factors *Actor Sex* and *Character Model* and between-subject factors *Participant Gender* and *Viewing Condition* to assess whether the experimental factors affect how participants perceive the Walk Ratio. The first ANOVA was applied on the absolute perceived Walk Ratio values and the second ANOVA was performed on the normalised values. As the sphericity assumption was met, no sphericity correction was applied to the data. When needed, Tukey post-hoc tests were performed for pairwise comparisons. Effect size was computed using partial eta squared ( $\eta_p^2$ ). Power analysis ( $\beta$ ) was performed based on effect size, sample size and significance values using G\*Power software.

To assess the effects of actor's height, weight and speed, we performed a multiple linear regression analysis with the Walk Ratio as independent variable and actor's height, weight and speed as predictor variables. Finally, to evaluate the accuracy of participants to recognize each actor's Walk Ratio, we also performed a one-sample Student t-test for each actor, comparing his/her Walk Ratio as estimated by participants on the corresponding character with his/her Walk Ratio computed from the walking motion captured at comfort speed (see Section 3.1.1).

## 4.3 Results

### 4.3.1 Perception of the Walk Ratio

Table 4.2 summarizes the effect of Actor Sex and Character Gender (Matched/Mismatched) on the perceived Walk Ratio. The Walk Ratio was highly influenced by the sex of the actor ( $p < 0.001$ ,  $\eta_p^2 = 0.494$ ,  $\beta = 0.95$ ) with male actors being on average associated with a higher Walk Ratio, as expected in our **H1** hypothesis. There were no difference on average when the motion was applied on the gender-matched or gender-mismatched virtual characters ( $p = 0.335$ ,  $\eta_p^2 = 0.039$ ), validating our **H3** hypothesis. A small interaction effect between Actor Sex and Character Gender was observed. Post-hoc analyses showed that there was no difference on average between Female and Male actors when their motions were applied on their respective gender-matched model, while differences

were found between female and male motions when both are applied on the female model, or the male model or when both are applied on their mismatched model (see Table 4.3). This indicates that male walking motions are associated on average with a higher Walk Ratio than females when the motions are applied on the same virtual character. We also found no difference according to the Viewing Condition ( $p = 0.950$ ,  $\eta_p^2 = 0$ ) suggesting that participants estimated a similar perceived Walk Ratio in screen or Virtual Reality conditions, invalidating hypothesis **H4**. Finally we did not find differences associated to the gender of the observers ( $p = 0.632$ ,  $\eta_p^2 = 0.01$ ).

Table 4.4 shows the results of the ANOVA on the perceived Walk Ratio when normalized by height. Similarly than for the non-normalized Walk Ratio, we found a main effect of Actor Sex ( $p < 0.001$ ,  $\eta_p^2 = 0.627$ ,  $\beta = 0.95$ ), no effect of Character Gender ( $p = 0.302$ ,  $\eta_p^2 = 0.627$ ), and a small interaction effect between Actor Sex and Character Gender ( $p = 0.021$ ,  $\eta_p^2 = 0.202$ ). Post-hoc analyses indicate that female Walk Ratios were perceived significantly higher than male Walk Ratios when normalized by height, for both gender-matched and gender-mismatched character models. There was however no difference between Female gender-matched and Female gender-mismatched, or between Male gender-matched and Male gender-mismatch. As in non normalized conditions, there was no effect of the viewing condition or participant gender.

Table 4.2: Main and interaction effects of Actor Sex, Character Gender, Viewing Condition and Participant Gender on the perceived Walk Ratio. Significant results are displayed in bold.

Factor	F-Test	p-value	$\eta_p^2$
<b>Actor Sex</b>	<b>23.4734</b>	<b>&lt;0.01</b>	<b>0.494</b>
Character Gender	0.9664	0.335	0.039
Viewing Condition	0.00404	0.950	0.0
Participant Gender	0.23509	0.632	0.01
<b>Actor Sex x Character Model</b>	<b>5.1587</b>	<b>0.032</b>	<b>0.177</b>

Figure 4.3 summarizes the results of the t-tests between captured Walk Ratios and Estimated Walk Ratios (only for gender-matched results). Participants estimated a statistical similar Walk Ratio for 6 of the 16 actors (F1, F3, M3, M4, M6 and M8). For all the other female actors, the Walk Ratio was over-estimated compared to the captured Walk Ratio. This pattern was not found for the remaining male actors. This partially invalidates hypothesis **H3**.

Table 4.3:  $p_{tukey}$  values of the post-hoc analysis of the interaction effect between Actor Sex and Character Gender. Significant results are displayed in bold.

	Female matched	Female mismatched	Male matched	Male mismatched
Female matched		0.108	0.152	<b>0.018</b>
Female mismatched	0.108		<b>&lt;0.001</b>	<b>&lt;0.001</b>
Male matched	0.152	<b>&lt;0.001</b>		0.774
Male mismatched	<b>0.018</b>	<b>&lt;0.001</b>	0.774	

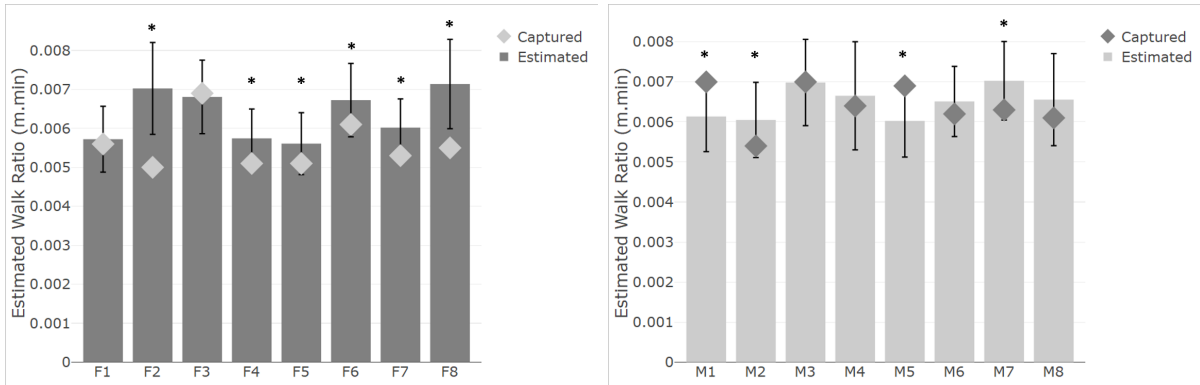


Figure 4.3: Estimated and captured Walk Ratios for the female (Left) and male (right) actors when their motion is applied on the gender-matched model. An star is displayed when t-test did not find significant difference between estimated and captured Walk Ratios.

Table 4.4: Main and interaction effects of Actor Sex, Character Gender, Viewing Condition and Participant Gender on the perceived normalised Walk Ratio. Significant results are displayed in bold.

Factor	F-Test	p-value	$\eta_p^2$
<b>Actor Sex</b>	<b>40.391</b>	<b>&lt;0.01</b>	<b>0.627</b>
Character Model	1.113	0.302	0.044
Viewing Condition	0.0003	0.985	0.0
Participant Gender	0.232	0.634	0.01
<b>Actor Sex x Character Model</b>	<b>6.065</b>	<b>0.021</b>	<b>0.202</b>

Figure 4.4 summarizes the results of the multivariable linear regression analysis with actor’s height, weight and speed as independent variables and perceived Walk Ratio as dependant variable. Together, the three independent variables predicted accurately the perceived Walk Ratio ( $R^2 = 0.725$ , Adjusted  $R^2 = 0.656$ ,  $F = 10.6$ ,  $p < 0.001$ ). However, when looking to the individual contributions of each predictors, actor’s speed was found to have a stronger influence ( $t = 5.542$ ,  $p < 0.001$ ) on the perceived Walk Ratio, than actor’s height ( $t = 1.269$ ,  $p = 0.228$ ) and actor’s weight ( $t = -0.441$ ,  $p = 0.667$ ) on the perception of the Walk Ratio which invalidates our **H2** hypotheses. This finding is further discussed in Section 4.4.

### 4.3.2 Eye Tracking Data

From the eye tracking data, we computed the percentage of time each body part was looked at by participants. Results are presented in Figure 4.5. We performed paired sample t-tests comparing each body part from one another. We found that body parts were all statistically observed a different percentage of time from one another, with legs being the most looked at (49.7% of the total time), followed by the arms (17.2%), the torso (11.9%) and the head (7.9%). The remaining 13.3% correspond to frames where the participants looked at the treadmill or the background.

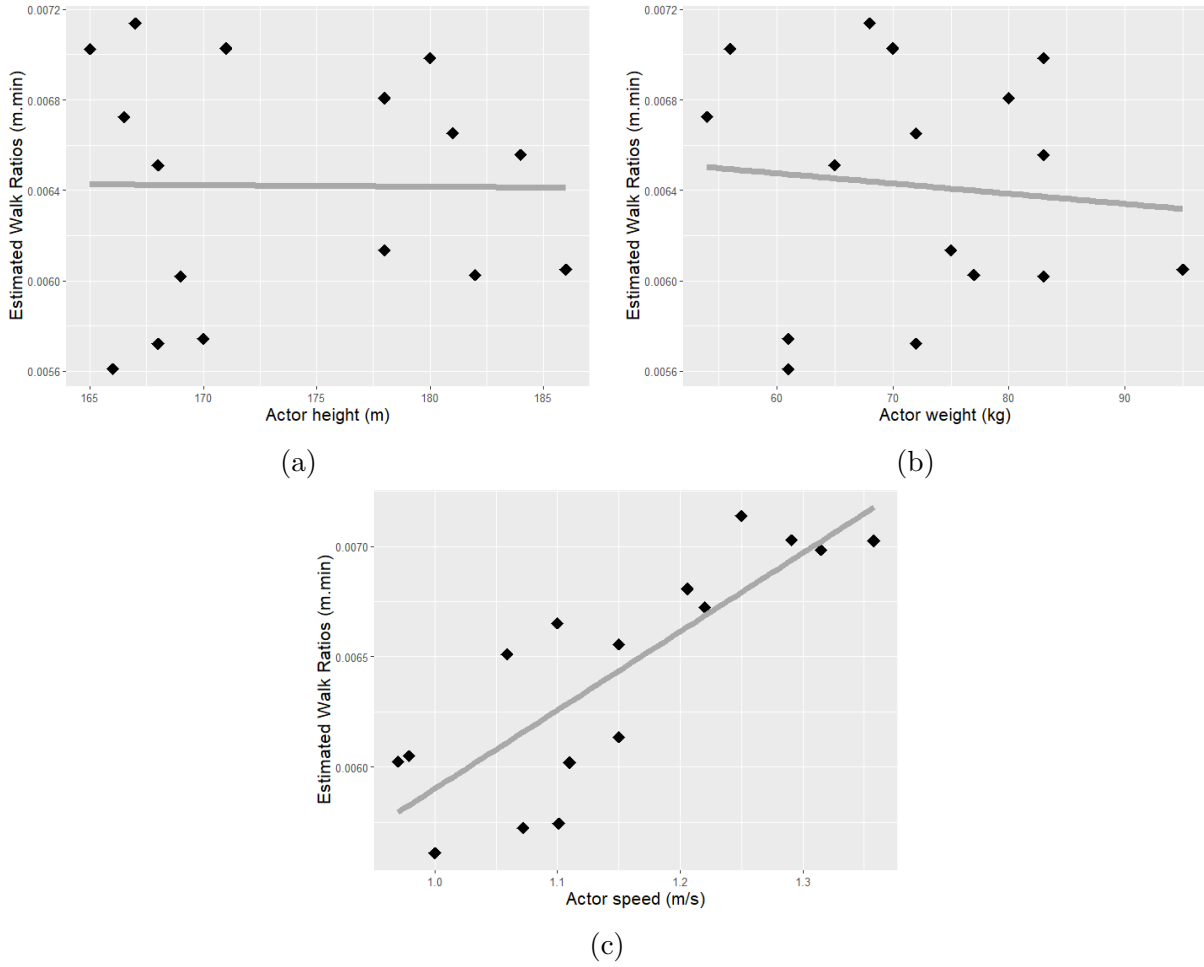


Figure 4.4: Results of the multivariable linear regression. While actor's height ((a),  $p=0.228$ ) and weight ((b),  $p=0.667$ ) could not predict accurately the perceived Walk Ratio, the speed of the actor was highly correlated to the perceived Walk Ratio ((c),  $p<0.001$ ).

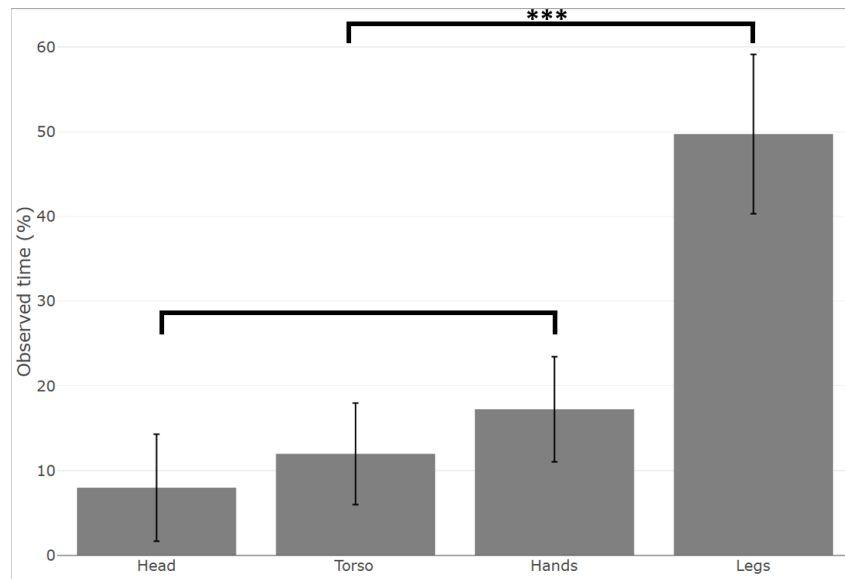


Figure 4.5: Percentage of time each body part was looked at by participants and standard error. Each body part is statistically different from one another

## 4.4 Discussion

### 4.4.1 Perception of the Walk Ratio

The main objective of this experiment was to explore further the results obtained in Chapter 3. In particular, we increased the number of actors from 4 to 16 with 8 females and 8 males of different height and weight and walking at different comfort speeds to investigate the relative effects of gender and morphology on the perception of the Walk Ratio. To determine if motion is more important than appearance in perceiving the Walk Ratio, we displayed the walking motion on two different virtual characters for each actor, one was matching the gender of the actor and one was not. We were also interested in evaluating the perception of the Walk Ratio in a Virtual Reality condition to investigate whether a more immersive display condition was associated with a more accurate evaluation of the Walk Ratio.

We first confirmed a gender difference in the perception of the Walk Ratios. When non normalised by height, female Walk Ratios were perceived to be significantly lower than male Walk Ratios. However, when looking only at gender-matched data, such a difference was not observed. This is a surprising result which does not confirm our original findings of Chapter 3. Also, we were expecting these differences to be present as the female actors were

shorter than their male counterpart which we expected to have a direct influence on step length. Thus, we decided to investigate the Walk Ratios independently of actors' height. After normalisation, we found that there was gender differences in the perceived Walk Ratio. Interestingly, female Walk Ratios were perceived higher than male Walk Ratios. This came also as a surprise as in the biomechanical literature, the gender differences in Walk Ratios tend to disappear after normalisation (Cho et al. 2004; Nagasaki et al. 1996; Sekiya et al. 1996). But this result suggests that the differences between perceived male and female Walk Ratios may be associated to morphological characteristics. We therefore explored other actor's features that could have impacted the perceived Walk Ratio by performing a linear regression on the estimated Walk Ratio with height, weight and walking speed as predictors. Surprisingly we found no effects of height or weight, which invalidates hypothesis **H2**, while we were expecting participants to associate smaller actors with a higher step frequency, resulting in a smaller Walk Ratio. Indeed, in the literature related to motion perception, Jokisch and Troje (2003) showed that observers were able to estimate the size of walking dogs from step frequency. In particular, they demonstrated that smaller dogs were associated with higher step frequencies. While we could not find similar perceptual studies for humans, we often hear that smaller persons need to have a higher step frequency to compensate for shorter step length as highlighted in the biomechanical literature (Senden et al. 2012). Regarding weight, even though it was different between the male and female groups, the mean Body Mass Index (BMI) was similar between the two groups. While it would be interesting though to explore more in depth the impact of BMI on the perceived Walk Ratio, it is difficult to find actors with extreme values of BMI. Furthermore, the highlighted BMI differences in the literature (see Chapter 2) are observed in the frontal plane, which would require to adapt our framework to enable the investigation of BMI on the perception of the Walk Ratio.

On the other hand we found a strong relationship between walking speed and perceived Walk Ratio (Figure 4.4). More specifically, we observed that an actor with a faster comfort walking speed was associated with a higher Walk Ratio perceived by observers. This is an interesting result, as we observed in Chapter 3 that for a given actor, the Walk Ratio was perceived similarly across speeds. This indicates that dynamic cues (walking pattern and speed) may be more important in evaluating the Walk Ratio of an actor than static cues (height, weight, gender). Indeed, Troje (2002) demonstrated that human observers rely more on dynamic information than structural information in a gender classification task of Point Light Display motions. However, in the same study, Troje showed that walking speed

did not provide demonstrative cues for the perception of biological motion. Thus, it is still unclear why we observe such a correlation between walking speed and Walk Ratio. It would be interesting to investigate wider ranges of walking speeds for different individuals with similar morphological characteristics. While Troje (2002) focused on Point Light Display gender discrimination, McDonnell et al. (2009) investigated the perception of the sex of virtual walkers when their motion is applied on gender-matched and gender-mismatched characters. They found that both body shape and motion influence the perceived sex. While being a different task than ours, these results indicate that both the actor structural information (height, weight, gender) and dynamic cues (walking pattern and speed) may impact the perceived Walk Ratio. To investigate these issues, we decided to apply the motions on two virtual characters whose gender was matching or not the actors' one. We found that the Walk Ratio was estimated similarly between the gender-matched and the gender-mismatched virtual characters for all the actors, validating hypothesis **H3**. This suggests that indeed, dynamic cues have more importance than static ones when evaluating the Walk Ratio, and that the Walk Ratio of an actor is perceived similarly when the motion is applied on different characters of the same height. However, it would be interesting to investigate other incongruous paradigm such as applying the same motion on characters with various morphologies.

For more than half of the actors, the Walk Ratio estimated by participants was significantly different from their captured Walk Ratio while still being in the range of natural Walk Ratios depicted in the literature (see Figure 4.6). More interestingly, only one female Walk Ratio was estimated to be lower than the natural Walk Ratio of the same actor. We found a more attenuated version of this pattern for male actors, with the Walk Ratio of three actors being lower than their captured one. One possible explanation might be related to the viewpoint used in our experiment. We used a side view to provide consistency between screen and HMD conditions. Although frontal and half frontal views are associated with a better recognition of one's motion (Jokisch et al. 2006), we decided to select this side view to provide a more intuitive control of the step frequency of the virtual characters than with a frontal view. Figure 4.7 presents the estimated and captured Walk Ratios of the 4 actors who were both used in the two experiments of Chapter 3 and Chapter 4 for both screen and VR conditions. F1 presents statistical differences between the viewpoint used in the first study and the viewpoint used in the second study, for both screen and VR displays. F2's Walk Ratio was estimated similarly across viewpoints and displays. M1 presents no differences between the viewpoints when the motion is displayed

on the screen but the VR condition was statistically different from the two screen conditions. M2 presents a statistical difference between the two screen conditions. F1, F2 and M1 were estimated more accurately in general in the side viewpoint than in the viewpoint used in the first contribution. Although many studies investigated the effect of viewpoint on biological motion perception, exploring different paradigms (Troje 2002), few of them explored its effect on the perception of characters in virtual reality. It would be interesting to follow up these results by exploring if this difference in viewpoint is associated with a difference in the perception of biological motion, or if a specific viewpoint enables participant to estimate more accurately the Walk Ratio.

Another result of our study supporting the idea of a viewpoint effect on the perception of the Walk Ratio is that we did not find any differences in the perceived Walk Ratio between the screen and virtual reality conditions, invalidating hypothesis **H4**. We specifically decided to recruit different participants for the two conditions to avoid any learning effect from the participants. As the same stimuli were used, participants could be able to recognize some features of specific actors that might affect their rating. Overall, these results indicate that a specific gait is associated with a specific perceived Walk Ratio, supporting the idea that personalised motions are critical when dealing with variety. This also indicates that a motion is equally rated as natural when presented through different display devices, also supporting the idea that the viewpoint may have more impact on the perception of the Walk Ratio than the display device. Exploring the effects of viewpoint on both VR and traditional screens would be thus very valuable to understand in which conditions participants are the more accurate in recognizing the Walk Ratio and thus improving the design of entertaining applications.

Finally, we were also motivated in evaluating where participants looked at in priority when estimating the Walk Ratio, which we performed using an eye-tacker built-in the HMD. As expected, we found that participants were mainly focusing on the legs when rating the naturalness of the motions, but other body parts were still considered. We however think that the character's arm segments fixation time was overestimated, as our chosen viewpoint implied to have the arm moving on the foreground for the participants. This leads to the arm passing periodically in front the torso and the upper leg segments, which can bias the actual amount of time participants observed the respective arm, torso and leg segments (see Figure 4.2). Nonetheless, legs were the segments most considered by participants, which suggests that when modifying virtual character motions to control how the character walks, the legs should be the main focus to obtain a believable modified

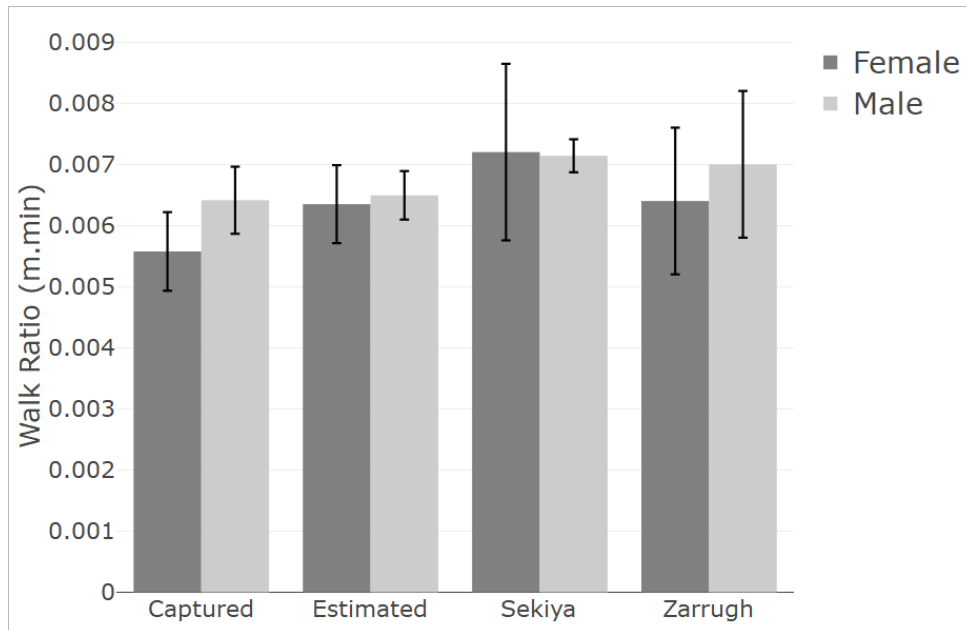


Figure 4.6: Estimated, Motion captured and Walk Ratios from Sekiya (1997), and Zarrugh (1974)

motion. That is why in the next Chapter, we investigate the use of a biomechanical parameter of the human walk to generate and edit walking leg motions.

#### 4.4.2 Guidelines for the control of virtual character walking animations

Following the results of Chapters 3 and 4, we propose different guidelines to help in the control of walking virtual characters. In our first study, we found that the Walk Ratio of an actor was perceived invariant across different walking speeds. Thus animators should consider keeping a constant step length to step frequency ratio when modifying the walking speed of a virtual character. For example increasing the walking speed would need to increase both step length and step frequency to maintain a constant Walk Ratio and thus a more natural motion. While we found that while the Walk Ratio was perceived invariant across speeds for a given individual in the first study, we also found in the second study that the perceived Walk Ratio was correlated with comfort walking speed when different actors were walking at their own walking speed. This implies that, when having two characters walking in a scene, a character displaying a faster comfort walking speed should also be associated with a higher Walk Ratio, and as a result longer steps

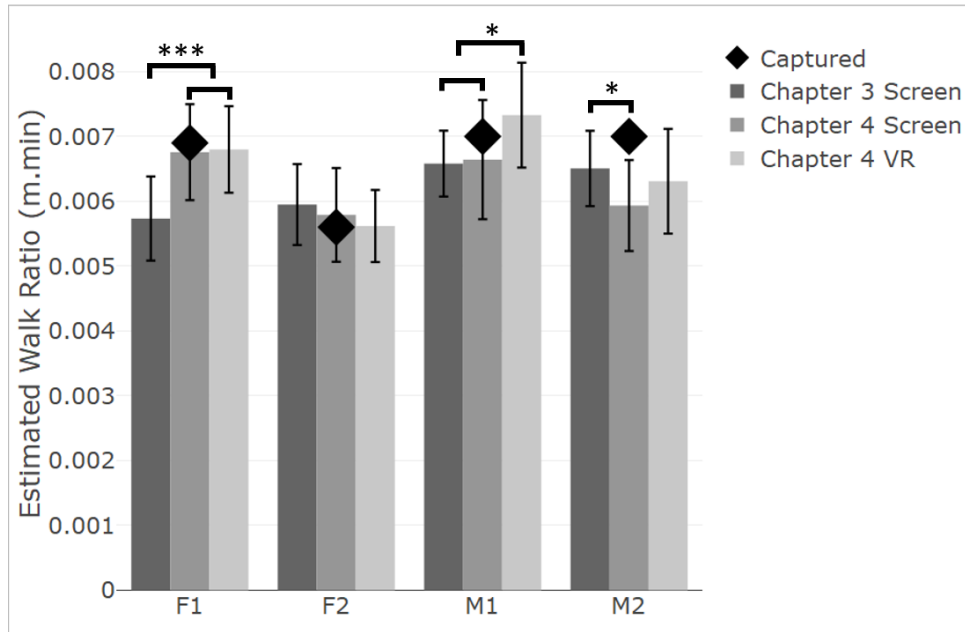


Figure 4.7: Captured and Estimated Walk Ratios of actors F1, F2, M1, M2 used in the experiments in Chapter 3 and Chapter 4. \* significant difference at the 0.05 threshold level, \*\*\* significant difference at the 0.001 threshold level.

than the slowest character. We also found in this study that the Walk Ratio was perceived similarly when presented on a gender-matched or a gender-mismatched virtual character. Combining this result with a viewpoint that limits the ability of observers to fully recognize the Walk Ratio might enable animators to more easily duplicate male motions on female virtual characters and vice versa to save valuable resources for the application.

# TOWARD EDITING LOWER BODY WALKING ANIMATIONS BASED ON BIOMECHANICAL PARAMETERS

---

## Contents

---

<b>5.1</b>	<b>Poulaine Analysis . . . . .</b>	<b>80</b>
5.1.1	Methods . . . . .	81
5.1.2	Results . . . . .	82
5.1.3	Discussion . . . . .	84
<b>5.2</b>	<b>Reconstruction and Evaluation . . . . .</b>	<b>87</b>
5.2.1	Reconstruction and Objective Evaluation . . . . .	87
5.2.2	Subjective Evaluation . . . . .	91
<b>5.3</b>	<b>Poulaine-based Motion Editing . . . . .</b>	<b>96</b>
5.3.1	Methods . . . . .	97
5.3.2	Task . . . . .	99
<b>5.4</b>	<b>Discussion and Future Works . . . . .</b>	<b>99</b>
5.4.1	Poulaine as a tool to edit motion . . . . .	99
5.4.2	Future Works . . . . .	100

---

As seen in Chapters 3 and 4, observers perceive gender, morphological and speed differences in the Walk Ratio when presented with walking virtual characters. We also found that when modifying walking motions using the Walk Ratio, observers focus their gaze on the legs of the characters. These combined results encouraged us to explore the creation of varied and personalised walking motions by using biomechanical parameters of the human leg. In biomechanics, early works from Marey (1894) uses ‘geometric chronophotography’ to describe the lower limb motion with the hip as the fixed reference point during human walking or running cycles. The particular shape produced by this representation of the

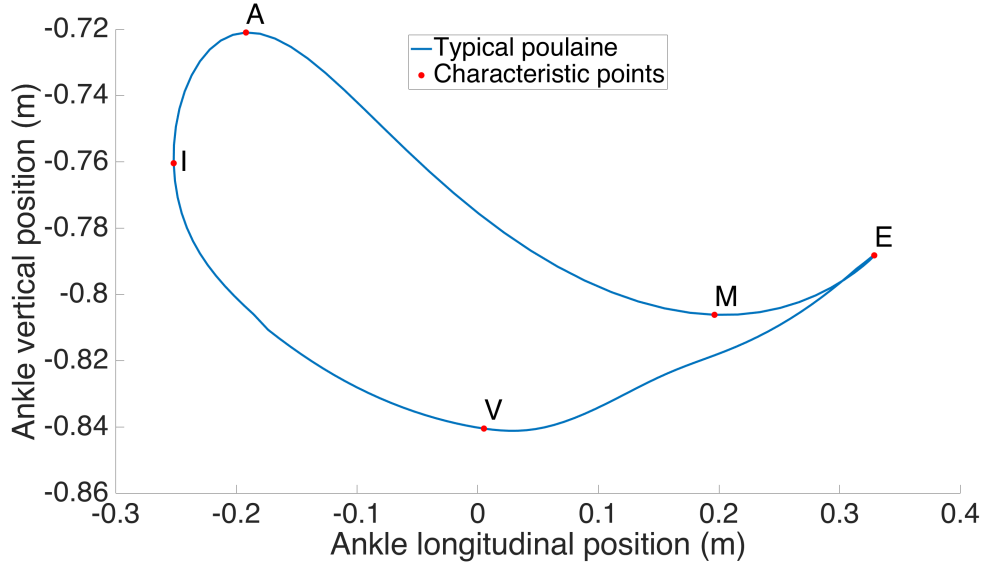


Figure 5.1: Characteristic points used for the analysis of the shape of the poulaine. E corresponds to the maximum extension of the leg, V to the moment where the ankle share the same vertical axis than the hip during the support phase, I to the maximum inflexion of the leg, A to the moment when the ankle reaches its maximum altitude and M to the local minima between A and E.

motion is often called the *poulaine* (Gajer et al. 1997), due to its likeness with a medieval shoe, but is also referred as the *ankle cyclogram* (Decker et al. 2006; Laumond et al. 2017) as seen in Figure 5.1. This representation of the ankle trajectory provides an explicit visual reading of the cyclical pattern of walking, but also visually highlights specific events of one's gait. For example, the maximum extension (E) and maximum inflexion (I) of the leg are the maximum and minimum values of the ankle trajectory on the longitudinal axis respectively (see Figure 5.2 (b) and (c)). Similarly, the maximum altitude (A) of the ankle trajectory corresponds to the maximum of the *poulaine* in the vertical axis. Finally, other specific events of the gait cycle such as the moments where the ankle and the hip share the same vertical axis (V) or the local minima corresponding to the middle of the swing phase (M) are directly accessible by reading the cyclogram, as seen in Figure 5.2. By its continuous and cyclic nature, the *poulaine* presents interesting characteristics for the study of human leg motion during walking and running (Whittle 1991). In particular, the biomechanical community used it to evaluate the running techniques of athletes during different sprinting tasks (Decker et al. 2006). Other biomechanical studies find an interest in using the *poulaine*. In particular, Pronost et al. (2005) proposed a methodology to

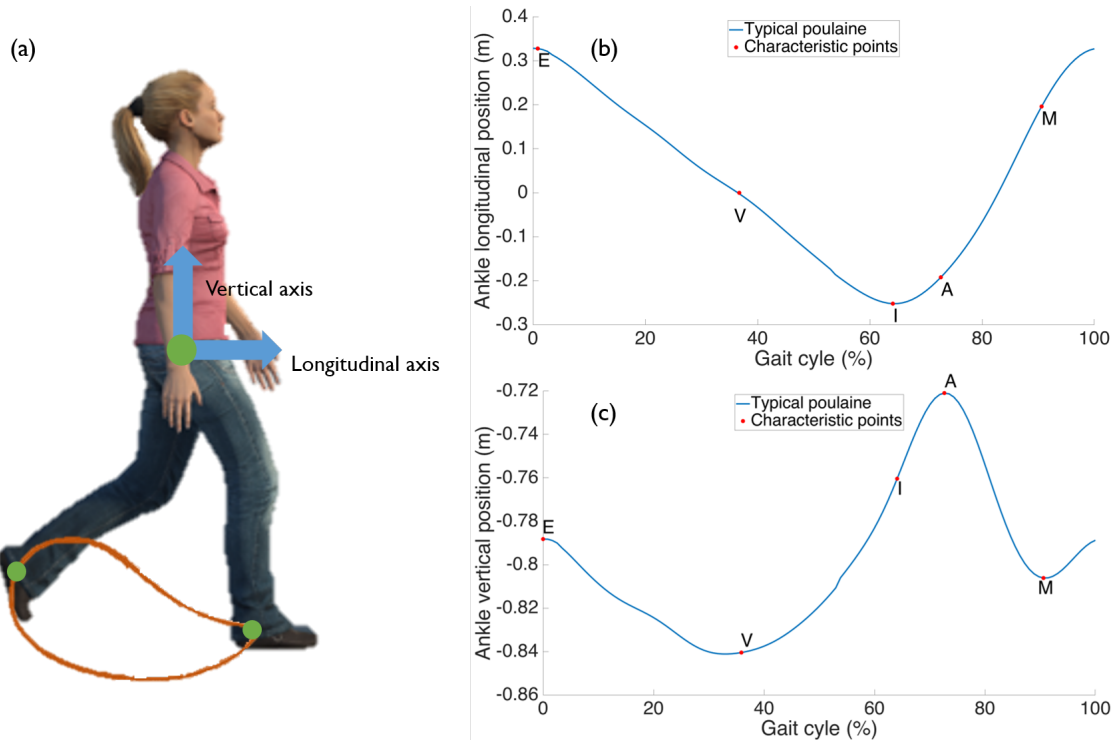


Figure 5.2: Ankle trajectory as seen in the hip reference frame (a). This biomechanical parameter is referred as the *poulaine*, or ankle cyclogram. Longitudinal (b) vertical (c) components of the *poulaine*.

reconstruct the bipedal whole body motion based on the *poulaine* and inverse kinematics. By modifying the *poulaine*, they showed that it was possible to adapt an input gait to a new target skeleton while respecting external constraints, such as foot positions. While they successfully demonstrated that their method can reconstruct bipedal locomotion, it has not been adapted to animate the motion of virtual characters in the context of Computer Animation. The main objective of this chapter is thus to study the potential use of the *poulaine* to generate natural walking leg motions for virtual characters. To create walking motions adapted to specific characteristics, we first investigate how the shape of the *poulaine* is modified according to both external (height, weight, gender) and internal (speed) parameters in Section 5.1 which have been showed to influence lower limb kinematics in the literature (Chehab et al. 2017; Moissenet et al. 2019). Then, we propose a framework to reconstruct and modify the leg motion based on the *poulaine* and the previously studied parameters in Section 5.2. Finally, we present a user study which goal is to evaluate the naturalness and accuracy of our approach and its potential use for Computer Animation in Section 5.3.

## 5.1 Poulaine Analysis

As mentioned in the introduction of this chapter, the *poulaine* has been widely studied in the context of sports performance. However, very few studies investigated how the shape of the *poulaine* evolves with respect to external (height, weight, gender) or internal (speed) parameters. Decker et al. (2007) proceeded to a normalisation of the ankle cyclogram to analyse the ankle trajectory differences between sprinters and middle stance runners at 14 spatiotemporal events of the running cycle. They demonstrated that a positive relationship exists between the size of the cyclogram and running speed, with sprinters depicting both a greater cyclogram size and running speed than middle stance runner. Whittle, in his introduction to gait analysis (1991), explains that foot trajectory is directly affected by parameters such as subject morphology, walking speed and step length, which indicates that the modification of one of these parameters implies the modification of the ankle trajectory. That is why Pronost et al. (2003; 2005) proposed an approach to generate plausible bipedal locomotion based on footprints, morphological data, and a reconstruction of the *poulaine*. In particular, they represented the *poulaine* as a set of four characteristic points (see Figure 5.1):

- E: the maximum extension of the leg
- V: the moment where the ankle and the hip share the same vertical axis during the support phase.
- I: the maximum inflection of the leg
- A: the moment when the ankle reaches its maximum altitude

By interpolating between those characteristic or control points, they reconstructed the 2D curve corresponding to the ankle trajectory. Finally, an inverse kinematic algorithm is applied with the newly generated *poulaine*, the step length (defined via the footprints) and the leg segments of the target skeleton as input parameters. Their approach allows not only to reconstruct walking motions, but also to modify them by adjusting the 2D position of the control points before the interpolation. However, no study investigated how the characteristic points must be modified according to the original actors characteristics, such as individual walking speed, height, weight or gender. Thus in this section, we propose a method to analyse how the shape of the *poulaine* is affected by these parameters.

### 5.1.1 Methods

To analyse the overall effect of walking speed, height, weight and gender, we used the database of Schreiber and Moissenet (2019). The database consists of 50 healthy young adults (24 F, 26 M age:  $37.0 \pm 13.6$  years) walking at various speeds on a 10 meter straight level walkway. Tree dimensional trajectories of 52 cutaneous reflective markers (placed as in Figure 5.3) were recorded using a 10-camera optoelectronic system sampled at 100 Hz (OQUS4, Qualisys, Sweden). Five subjects were removed from the analysis due to missing marker data on the ankle. While 5 different walking conditions were recorded (0-0.4 m/s, 0.4-0.8 m/s, 0.8-1.2 m/s, self-selected natural speed, self-selected fast speed), we only used the data where the walking speed was greater than 0.8 m/s as lower speeds are associated with a different gait pattern (Murakami and Otaka 2017) that could affect the analysis of a more ‘natural’ *poulaine*, we therefore obtained a total of 135 walking motions with speeds varying from 0.80 to 2.25 m/s. Each recorded motion contains at least one full gait cycle, and was exported as C3D file<sup>1</sup>. We used The Matlab R2018b software and the Biomechanical Toolkit<sup>2</sup> to load and extract the marker information of each C3D file.

From the marker trajectories, we computed the 2D *poulaines* in the sagittal plane. As our objective is to evaluate how different characteristic points of the *poulaine* are influenced by external/internal factors, we chose to extract a number of characteristic points. Our goal is also to select characteristic points that are easy to control from animation point of view while enabling a good quality of reconstruction. We thus decided to use the 4 characteristic points proposed by Pronost et al. (2005) in addition to a fifth characteristic point. This fifth characteristic point represents the local minima corresponding to the middle of the swing phase. The 5 points used are summarised in Figure 5.1. For each motion, we computed the 5 characteristic points of the *poulaine* and the walking speed. Age, Gender, Height and Weight of each participant were retrieved from the meta data of the C3D files and summarised in Table 5.1 with the different computed walking speeds and the Body Mass Index (BMI) computed from the Height and Weight data. For each of the characteristic points’ longitudinal and vertical positions, we performed a linear regression with age, height, weight, gender and speed as predictive variables to evaluate their relative effects. From the linear regression we want to compute the expected position of each control point as a linear combination of the predictors. In particular we search the different  $b_i$  coefficients predicting the position  $Y$  of the characteristic point using the

---

1. <https://www.c3d.org/>

2. <https://code.google.com/p/b-tk/>

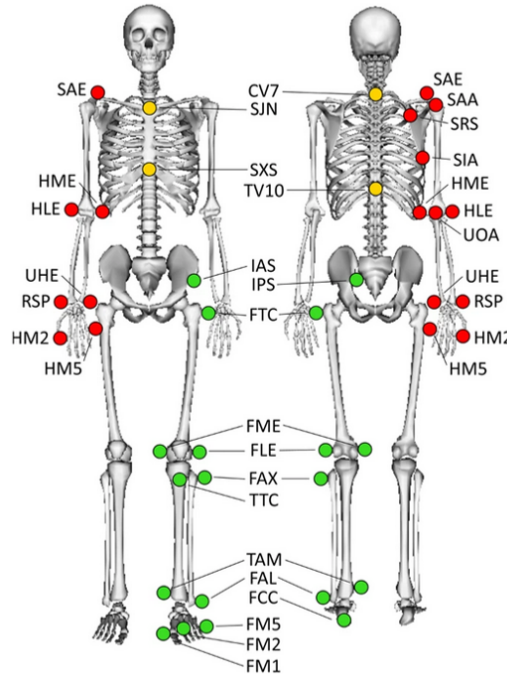


Figure 5.3: Marker set used by Schreiber and Moissenet (2019) to motion capture their subjects

following equation:

$$Y = b_0 + b_1.age + b_2.Height + b_3.Weight + b_4.Gender + b_5.Speed \quad (5.1)$$

### 5.1.2 Results

Table 5.1 summarises the Age, Height, Weight, BMI and different walking speeds of the actor database from Schreiber and Moissenet (2019). *Height*, *Weight* and *BMI* were statistically different between the male and female subjects, with male subjects being taller, heavier and with a higher BMI than female subjects. No difference in age or speed was found between the groups. As height was significantly different between male and female subjects, we decided to perform two different linear regression analyses. In the first analysis, we want to observe the ‘raw’ data to understand the global distribution of each characteristic points. In the second analysis, we focus more on the normalised data to understand the relative contribution of each predictor. Normalisation of the characteristic points’ position and the walking speed was performed using the leg length ( $l_0$ ) of the subject as described in (Hof 1996) and (Pinzone et al. 2016) i.e:

Table 5.1: Summary of the actor database used for our analysis. Height, Weight and Body Mass Index (BMI) were significantly different between female and male subjects.

	Female	Male	F statistic	p value
N	21	24		
Age (years)	37.9±13.7	37.2±13.6	0.103	0.749
Height (m)	<b>1.66±0.05</b>	<b>1.80±0.06</b>	<b>184</b>	<b>&lt;0.001</b>
Weight (kg)	<b>63.8±7.1</b>	<b>79.6±10.3</b>	<b>112</b>	<b>&lt;0.001</b>
BMI (kg/m <sup>2</sup> )	<b>23.0±2.41</b>	<b>24.4±2.59</b>	<b>10.6</b>	<b>=0.001</b>
Average Slow Speed (m/s)	0.95±0.08	0.99±0.10	1.56	0.218
Average Normal Speed (m/s)	1.16±0.11	1.14±0.15	0.154	0.696
Average Fast Speed (m/s)	1.60±0.18	1.60±0.22	6.24e-4	0.980
Average All Speeds (m/s)	1.23±0.26	1.25±0.31	0.0163	0.898

$$X_{norm} = X/l_0 \quad (5.2)$$

and :

$$Speed_{norm} = Speed/\sqrt{g.l_0} \quad (5.3)$$

with  $g$  the standard acceleration due to gravity. Leg lengths were retrieved from the meta data of the database of Schreiber and Moissenet (2019).

Figure 5.4a represents the position of the different control points and the mean *poulaine*. The linear regression analysis focuses on analysing both the longitudinal and vertical positions of each characteristic point, which main results are summarized in Table 5.2. Each regression coefficient was computed as the quadratic error between the original values and the predicted ones. From the linear regression results, only two positions of the characteristic point were not or poorly explained by the predictors: the longitudinal position of the characteristic point V, which by definition is always 0, and the longitudinal position of the characteristic point M. *Weight* was never a significant predictor for any of the control points while *Age* was barely significant for only two control points. *Height* was found to be a significant predictor for the vertical position of all the control points and for the longitudinal position of the characteristic point M. *Gender* was found to be a significant predictor for the longitudinal position of points E, I, A and M and for the vertical component of points E and M. Finally *Speed* was found to be a significant predictor for the the longitudinal and vertical positions of characteristic points E, I and A and the vertical

Table 5.2: Regression analysis of each axis component of all the characteristic points using Age, Height, Weight, Gender and walking speed as predictors

Control Point	Axis	Intercept b0	Age b1	Height b2	Weight b3	Gender b4	Speed b5	Adjusted R <sup>2</sup>	RMSE	p value
Maximum	X	0.022	NS	NS	NS	-0.054	0.103	0.28	0.055	<0.001
Extension (E)	Z	0.182	-6.42E-04	-0.606	NS	-0.024	0.056	0.77	0.034	<0.001
Ankle Vertical to	X	0.006	NS	NS	NS	NS	NS	NS	NS	NS
Hip (V)	Z	0.198	NS	-0.623	NS	NS	NS	0.91	0.017	<0.001
Maximum	X	0.153	NS	NS	NS	-0.061	-0.086	0.41	0.058	<0.001
Inflexion (I)	Z	0.154	NS	-0.602	NS	NS	0.038	0.77	0.025	<0.001
Maximum	X	0.200	NS	NS	NS	-0.055	-0.093	0.34	0.064	<0.001
Altitude (A)	Z	0.127	NS	-0.546	NS	NS	0.034	0.76	0.024	<0.001
Local Minima (M)	X	0.004	NS	0.139	NS	-0.027	NS	0.08	0.025	0.005
	Z	0.164	-4.14E-04	-0.573	NS	0.013	0.014	0.87	0.022	<0.001

position of point M. When analysing in the details the different weights of each predictor (i.e. the different  $b_i$  values), *Height* has more importance as a predictor than *Gender* and *Speed*.

Results of the linear regression on the normalised data are presented in Table 5.3. *Age* and *Weight* were almost not influencing the longitudinal and vertical position of the characteristic points. *Gender* was a significant predictor for the longitudinal positions of characteristic points E, I, A and M and for the vertical positions of characteristic points E, V, and M. The *Normalised walking speed* was a significant predictor of all the vertical positions and the longitudinal position of characteristic points E, I and A. In this height normalised analysis, *Speed* was a more important predictor than *Gender* when comparing their respective weights. Figure 5.4b represents the position of the different characteristic points and the mean *poulaine* when normalized by leg length. In comparison with the raw data, the characteristic points of the normalised *poulaine* present less dispersion in their distribution and for 4 of them a linear pattern tendency appears.

### 5.1.3 Discussion

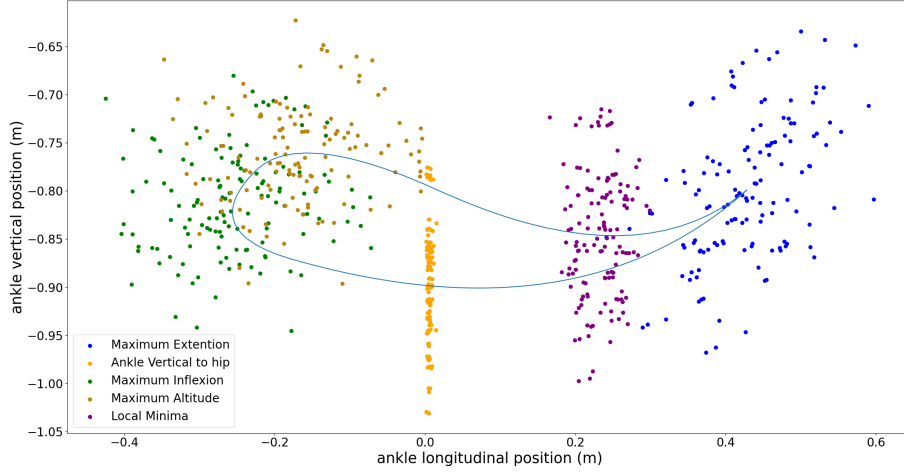
The analysis of a number of characteristic points of the *poulaine* demonstrated that *Height*, *Gender* and *Speed* were metrics correlated with the positions of these characteristic points. This is in agreement with related studies that use linear regression analysis to predict gait patterns from high levels predictors (Chehab et al. 2017; Moissenet et al. 2019). As height was found to be an important predictor of the evolution of the *poulaine*, we decided to perform a second analysis, in which we normalised the positions of the

Table 5.3: Regression analysis of each axis component of all the characteristic points normalised by the stature of the actors using Age, Weight, Gender and normalised walking speed as predictors

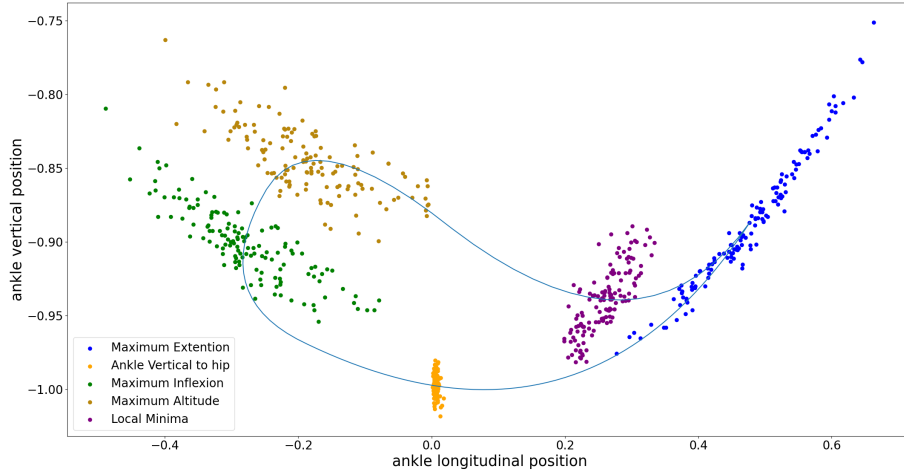
Control Point	Axis	Intercept b0	Age b1	Weight b2	Gender b3	Speed Normalised b4	Adjusted R <sup>2</sup>	RMSE	p value
<b>Maximum Extension (E)</b>	X	0.322	-9.40E-04	NS	-0.069	0.336	0.37	0.061	<0.001
	Z	-0.968	-5.55E-04	NS	-0.039	0.182	0.36	0.003	<0.001
<b>Ankle Vertical to Hip (V)</b>	X	-0.002	NS	NS	NS	NS	NS	NS	NS
	Z	-0.992	NS	NS	-0.005	-0.021	0.20	0.006	<0.001
<b>Maximum Inflexion (I)</b>	X	-0.131	NS	NS	-0.073	-0.287	0.31	0.065	<0.001
	Z	-0.994	NS	4.58E-04	NS	0.123	0.29	0.021	<0.001
<b>Maximum Altitude (A)</b>	X	-0.010	NS	NS	-0.070	-0.313	0.28	0.071	<0.001
	Z	-0.920	NS	NS	NS	0.109	0.24	0.020	<0.001
<b>Local Minima (M)</b>	X	0.287	NS	NS	-0.032	NS	0.22	0.028	<0.001
	Z	-0.939	-2.62E-04	NS	-0.022	0.042	0.34	0.018	<0.001

characteristic points and the walking speeds by the leg length of the subjects to better analyse the contribution of the other predictors. In this second analysis, we found that the positions of the characteristic points were still well predicted by *Gender* and *Speed* with the latter having a higher influence than the former. We also found that *Age* and *Weight* were not significant predictors for the shape of the *poulaine* in both normalised and non normalised conditions. The age range of the database used was between 19 and 67 years old. In the literature review, we pointed out that the effect of age on gait pattern was in older or younger subjects that the range used in the database, explaining the absence of an effect of the age in our analysis. However, human motion studies demonstrated that walkers beyond 65 years old and younger than 7 years old are associated with different gait patterns than walkers within this range (JudgeRoy et al. 1996; Ganley and Powers 2005; Gouelle et al. 2016). It has also been showed that age is a predictor of human walking motion (Chehab et al. 2017; Moissenet et al. 2019). To improve our linear regression analysis, it would be interesting in the future to investigate wider ranges of both age and weight to have a better understanding of potential relationships between the *poulaine* and these metrics.

Our main objective in this contribution is to control the shape of the *poulaine* to synthesize walking animations with defined characteristics influencing the characteristic points. Thus, it requires first to validate the methodology to reconstruct and modify the *poulaine* and walking animations, which is our objective in the next section.



(a) Distribution of the characteristic points and mean Poulaine



(b) Distribution of the normalised characteristic points and mean Poulaine normalised by height

Figure 5.4: Mean poulaine and distribution of the characteristic points when (a) non normalised by the stature of the participant, (b) normalised by the stature of the participant.

## 5.2 Reconstruction and Evaluation

Our analysis of the influence of several parameters on the vertical and longitudinal position of characteristic points of the *poulaine* is interesting in the context of computer animation. More specifically, controlling the shape of the *poulaine* would enable us to synthesize animations adapted to one's characteristics. While the analysis of the vertical and longitudinal position of the characteristic points presented in the previous section informed on how the shape of the *poulaine* is influenced according to various features, we are now interesting in controlling these characteristic points to synthesize walking animations from this kinematic variable. In this section, we present and evaluate a framework to synthesize walking animation based on the *poulaine* and inverse kinematics.

### 5.2.1 Reconstruction and Objective Evaluation

Combining trajectory of the ankle and inverse kinematics is a very common and fast technique to produce natural walking motions. As seen in Chapter 2, given a set of positions of end-effectors, inverse kinematics solves the position and orientation of all the joints in a given hierarchy. However, its use in virtual character animation is often reduced to constrain foot position in combination with other animation generation algorithms. Here we propose to use inverse kinematics as the main algorithm driving the motions of our virtual characters. In particular, we adapt the framework of Pronost et al. (2005) to animate the lower body of virtual characters from the *poulaine*. Briefly, the main idea is to represent the *poulaine* as a set of control points and to interpolate these control points using standard approaches (e.g. splines) to reconstruct the *poulaine* curve. Finally, an inverse kinematics algorithm uses the *poulaine* as the end-effector trajectory to reconstruct the position and orientation of the knee and hip joints. However, as both the number of control points and the interpolation method can have an influence on the reconstructed *poulaine* trajectory, and therefore on the walking animation, we propose and evaluate in this section several methods to reconstruct the *poulaine* based on different control points and interpolation techniques.

### Methods

For the purpose of the analysis, we recorded the motion of 4 actors (2 females, 2 males, age: avg=28, min=25, max=36, height: avg=1.78, min=1.65, max=1.86) performing 15-meter straight walks at 5 different walking speeds (e.g., very slow, slow, comfort,

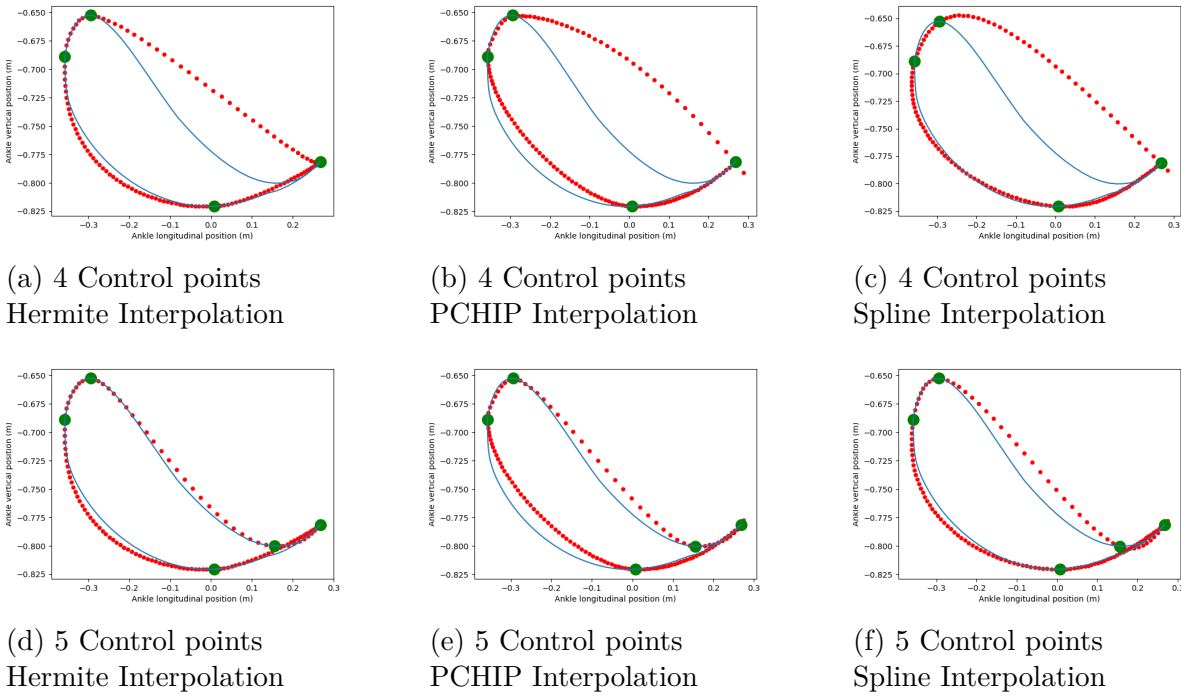


Figure 5.5: Different reconstructions of the same poulaine using different combinations of control points and interpolation technique. The blue curve corresponds to the original poulaine, the red curve to the reconstructed poulaine and the green dots to the control points used for the reconstruction.

fast and very fast) using a Xsens IMU-based motion capture system at a sampling rate of 120 Hz (see Figure 3.1). We always recorded the comfort walking motion first, then we recorded the motions at fast and very fast or slow and very slow walking speed. We then asked participants to walk at comfort speed before recording the last two walking motions, resulting in a total of 20 motions (4 Actors, 5 Speeds). For each motion, we computed the 2D *poulaine* in the sagittal axis and the 5 characteristic points presented in Section 5.1.1, which will be used as control points for the reconstruction. To evaluate the influence of the number of control points, we decided to reconstruct the *poulaine* using either these 5 control points, or only the 4 control points proposed by Pronost et al. (2005). First the *poulaine* was separated according to its longitudinal and vertical components (see Figure 5.2 (b) and (c)). Then the reconstruction of each component was performed using 3 different interpolation techniques presented below (**Spline** interpolation, **PCHIP** interpolation and **Hermite** interpolation) using the set of 4 of 5 control points. Figure 5.5 shows a typical reconstruction of one of our *poulaine* using the different combination of control points and interpolation technique. For each of the reconstructed curve, we computed the root mean square error (RMSE) between the reconstructed and original *poulaines*. We hypothesize that the *poulaines* interpolated with 5 control points will be associated with lower RMSE values, as interpolators often perform better with a higher number of control points. We also hypothesize that Hermite interpolation will be associated with a lower RMSE value, as explained below. To evaluate the accuracy of our reconstruction method, we performed a 2-way repeated-measures Analysis of variance (ANOVA) with factors *Number of Control Points* and *Interpolation technique*. Effect size was computed using partial eta squared ( $\eta_p^2$ ). When needed, Tukey post-hoc tests were performed for pairwise comparisons.

### Interpolation techniques

We decided to use 3 different 1-dimensional interpolation techniques to reconstruct the *poulaine*. Each of these techniques is based on a cubic interpolation (third degree polynomial) with different input parameters. In particular, their objective is to find the best polynomial of degree 3 preserving specific constraints (control points' positions and local derivatives).

- Cubic spline interpolation (called **Spline** in this contribution) interpolates control points with a piecewise cubic polynomial which is twice continuously differentiable. In the Python implementation of this interpolation method, only the positions of

the control points are required and thus the solution is sought as a parabola passing through given points.

- Piecewise Cubic Hermite Interpolating Polynomial (**PCHIP**), uses monotonic cubic splines to find the value of new points. In the Python implementation of this method, only the positions of the control points are required. The first derivatives are computed by the PCHIP algorithm (Fritsch and Butland 1984). The first derivatives are guaranteed to be continuous, but the second derivatives are not necessarily guaranteed to be continuous.
- Cubic Hermite Spline (**Hermite**) is also a Piecewise-cubic interpolator matching control points' positions and first derivatives. Each piece is a third-degree polynomial specified in Hermite form. In its Python implementation, this interpolation requires both the position and derivative of each control points ensuring the continuity of these parameters on the interpolated curve.

We hypothesize that Spline interpolation will be performing the worst interpolation, followed by PCHIP interpolation then by Hermite interpolation. Indeed, in its Python implementation, Spline interpolation will approximate derivatives by a parabola regardless of the actual values of the derivatives of the control points, while PCHIP's Python implementation computes these derivatives using the algorithm of Fritsch and Butland (1984) ensuring continuity of the first derivatives but not necessarily ensuring continuity of the second derivatives. Hermite's Python implementation interpolation is provided with the first derivatives and ensures both first and second derivatives continuity.

## Results and Discussion

Table 5.4 and Figure 5.6 summarise the main results of our analysis. There was a main effect of both the Number of Control Points ( $p = 0.003$ ,  $\eta_p^2=0.532$ ) and the Interpolation technique ( $p<0.001$ ,  $\eta_p^2=0.686$ ) used, but no interaction effect. In particular, post-hoc analysis shows that *interpolations using 5 control points are associated with a lower RMSE*. We were expecting these results as interpolation techniques typically show more accuracy when more well chosen control points are provided for being interpolated. Furthermore, post-hoc analysis also showed that *Hermite interpolation was associated with the lowest RMSE, followed by PCHIP Interpolation then by Spline Interpolation*. This is probably due to the characteristics of each interpolation. Splines only requires the position of the control points but does not ensure continuity of the first derivative. PCHIP interpolation

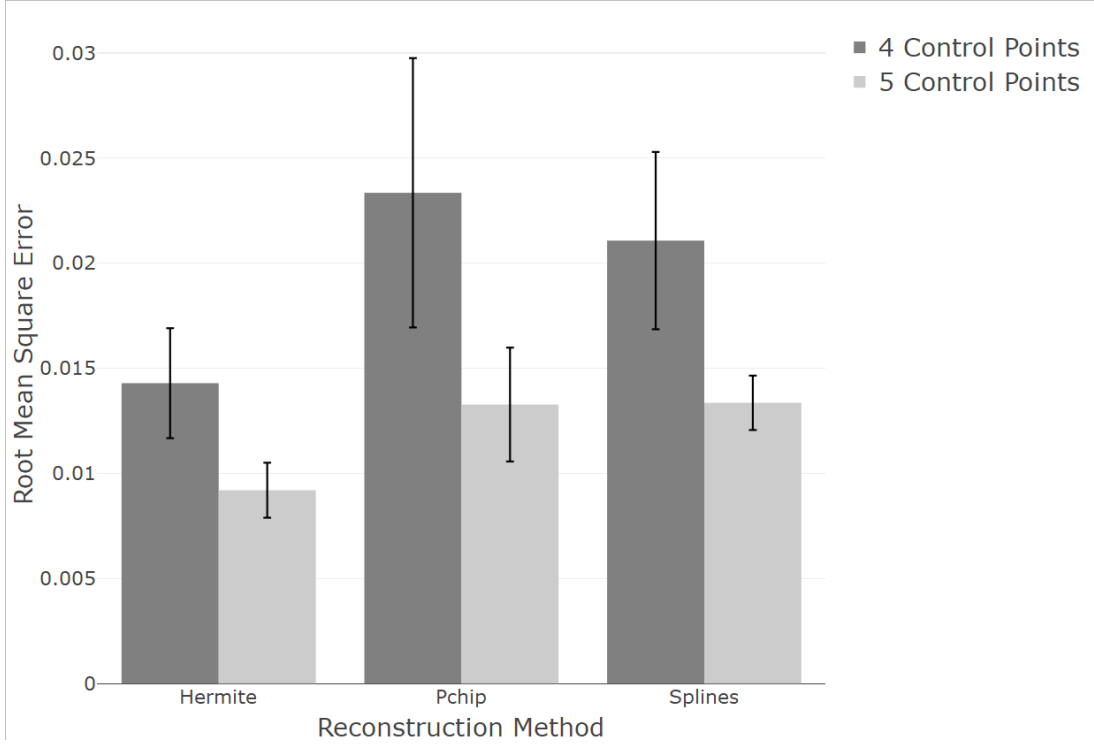


Figure 5.6: Root mean square error for each combination of *number of control points* and *interpolation technique*, averaged over 20 motion clips from our database.

provides continuity of the first derivative but not necessarily the continuity of the second derivative. Hermite interpolation keep continuity of the two-first derivatives. Thus, more information is available when reconstructing curves using Hermite interpolation, which explains the lower RMSE. However, a lower RMSE does not ensure that the visual quality of the lower-body motion will be superior when the final animations are presented to observers. Thus, we investigate in the next section the visual quality of the leg’s walking motions produced from the different interpolated techniques and control points

### 5.2.2 Subjective Evaluation

In this section, we present a user study investigating the visual quality of lower body motions generated with different interpolation methods and numbers of control points.

#### Stimuli preparation

We selected the slow, comfort and fast walking speed motions from the recorded data presented in Subsection 5.2.1. For each motion, we then extracted the different control

Table 5.4: Main results of our method to reconstruct the *poulaine* from control points and interpolation.

Factor	F-test	p value	$\eta_p^2$
<b>Number of Control Points</b>	<b>13.62</b>	<b>0.003</b>	<b>0.532</b>
<b>Interpolation technique</b>	<b>13.09</b>	<b>&lt;0.001</b>	<b>0.686</b>
Number of Control Points x Interpolation technique	1.63	0.237	0.213

points from the ground truth *poulaine* trajectory, and reconstructed the the ankle trajectory using the 3 interpolators presented in the previous section and using both 4 and 5 control points. Then lower body animations were reconstructed using inverse kinematics to satisfy the new ankle trajectories. Thus, a total of 72 lower body walking motions were generated and used as stimuli for our experiment (4 actors, 3 speeds, 2 sets of control points and 3 interpolation techniques). The motions were created using Pynimation<sup>3</sup>, a custom Python program, in which we retargeted the motions to a virtual character which height's was scaled according to each corresponding original actor and then exported to the Unity (2019.4.20f1) game engine in which we designed the perceptual experiment.

### Task and Participants

Participants were presented with two side-by-side animations, focusing on the lower body movements (see Figure 5.7). Participants were asked to indicate which motion was the most natural in their opinion using a two alternative forced choice design. The two animations presented on screen always consisted in one animation reconstructed using one of the method presented before, as well as the original captured animation. As our method only modifies the lower body motion, we decided to choose a viewpoint focusing the visual attention of the user on the legs, as seen in Figure 5.7. Each motion was randomly presented on the left or right part of the screen. No information about naturalness of the motion was given to the participants. Although there was no time limit to select the more realistic motion, participants were informed that response time was measured. A total of 21 participants (11 females, 10 males) participated in the experiment. They were all naive to the purpose of the experiment and gave written consent. As the experiment took place during the lockdown period, the experiment was performed remotely and screen size used by the participants for the experiment was recorded.

3. <https://lhoyet.gitlabpages.inria.fr/pynimation/>



Figure 5.7: Viewpoint of the perceptual experiment comparing the different interpolation methods. The framework always consisted in observing both a captured motion and a reconstructed motion, randomly positioned on the left or right

## Analysis and Statistics

From the participant answers, we computed the probability of selecting animations reconstructed with each method over the ground truth animation. We also computed the time spent by participants to select the motion they considered to be the most natural. Statistical analysis was performed using the Jamovi software. Significant level was set at the 95% level (i.e.,  $p < 0.05$ ). Normality was assessed using Shapiro-Wilk test. We performed a five-way repeated measure analysis of Variance (ANOVA) with *Number of control points*, *Interpolation Method*, *Speed* and *Actor* as within-subject factor and *Participant Gender* as between-subject factor on the probability of selecting the reconstructed motion over the ground truth. We performed a second five-way repeated measure ANOVA on the response time with *Number of control points*, *Interpolation Method*, *Speed* and *Actor* as within-subject factor and *Participant Gender* as between-subject factor. As there was a violation of the sphericity assumption (*Interpolation Method*  $p < 0.05$ , *Actor*  $p < 0.05$ , *Speed*  $p < 0.05$ ) we applied Greenhouse-Geisser correction to the data. Effect size was computed using partial eta squared ( $\eta_p^2$ ). When needed, Tukey post-hoc tests were performed for pairwise comparisons.

Table 5.5: Main results of our perceptual experiment on the generation of walking leg motions from the poulaine. Significant results are displayed in bold.

Factor	F-test	p value	$\eta_p^2$
<b>Number of Control Points</b>	<b>45.99</b>	<b>&lt;0.001</b>	<b>0.708</b>
Interpolation technique	1.43	0.25	0.07
Actor	0.868	0.463	0.044
Speed	0.752	0.478	0.038
Participant Gender	0.0014	0.971	0

Table 5.6: Time results of our perceptual experiment. Significant results are displayed in bold.

Factor	F-test	p value	$\eta_p^2$
<b>Number of Control Points</b>	<b>47.15</b>	<b>&lt;0.001</b>	<b>0.713</b>
<b>Interpolation technique</b>	<b>15.21</b>	<b>&lt;0.001</b>	<b>0.445</b>
Actor	0.353	0.787	0.018
Speed	0.370	0.693	0.019
Participant Gender	<0.0001	0.994	0

## Results

Table 5.5 and Figure 5.8 summarize the main results of the perceptual experiment. We found that the number of control points was highly influencing the confusion rate between the reconstructed and motion capture motion ( $p < 0.001$ ,  $\eta_p^2 = 0.708$ ), with *Motions generated using a poulaine reconstructed using 5 control points were more often confused with ground truth motions than those using a poulaine reconstructed with 4 control points*. We found no significant difference associated to the interpolation method, indicating that overall *all the interpolation methods were associated with a similar confusion rate*. We found no effect of the actor or speed, indicating that perception of the naturalness of the motion was more due to the reconstruction method rather than actor’s characteristics. Table 5.6 presents the main results of the same study on the time variable. We found that the number of control points ( $p < 0.001$ ,  $\eta_p^2 = 0.713$ ) and the interpolation technique ( $p < 0.001$ ,  $\eta_p^2 = 0.445$ ) used highly affected the response time of the participant. In particular, participants spent more time to select the motion they considered to be the most natural when the ground truth was compared with motions generated with 5 control points. Moreover participants spent more time to select the motion they considered the most natural when the ground truth was compared with motions generated with Hermite interpolation,

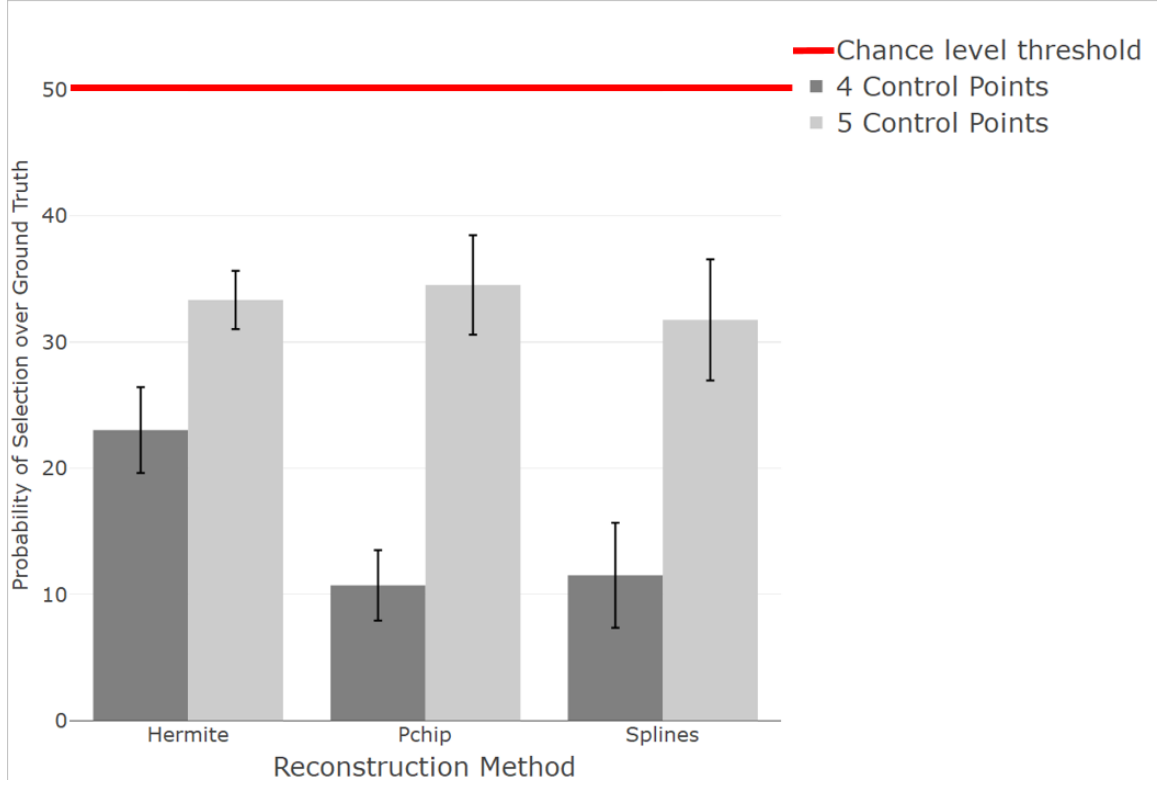


Figure 5.8: Results of the Perceptual Experiment

compared to PCHIP and Spline interpolations. We found no time difference related to the speed, the actor displayed, or participant's gender. Combined together, these results indicate that Hermite interpolation with 5 control points seems to be more suitable to reconstruct the *poulaine*, as for a similar probability of selecting a reconstructed motion over the ground truth this method requires a longer response time from participants, compared to PCHIP or Spline Interpolation. Furthermore, when comparing the objective and subjective evaluations of the reconstructed *poulaine*, Hermite interpolation presents the lower RMSE for a similar confusion rate than the other two interpolation methods. However, when observing the absolute values of the confusion rate we observe that the method with the highest confusion rate is close to 35%, still far from 50% chance level threshold.

### 5.3 Poulaine-based Motion Editing

In this section, we propose a framework to explore the use of the *poulaine* to edit walking animations. In particular, as we found an important influence of speed on some characteristic points of the *poulaine*, we propose to explore the application of the method described in the previous sections to edit walking animations to novel speeds. In the literature, this process is typically performed using different techniques which we propose to compare to. In particular, two techniques widely used in computer animation are interesting for us to compare with.

Motion blending is a technique consisting in blending between different motions to generate a new one with characteristics which depend on the blending weights applied to each source motion. This is the approach we used in Chapter 3 and 4 to generate motions at specific speeds and step frequencies. For example, to generate a walking motion at 1.5m/s using two input motions at 1.0m/s and 2.0m/s, blending algorithms will equally distribute the part of each motion to obtain the desired speed of 1.5m/s. While this technique can produce natural motions very efficiently, it suffers from the need of a database with a wide range of walking speeds to be able to generate all the intermediate motions and cannot extrapolate to walking speeds outside the range of the database. The wider the range of walking speeds of the input motion the more intermediate motions can be generated. However, blending between too extreme motions may lead to unnatural behaviours. Indeed, walking patterns are different between very slow and very high speeds as seen in Chapter 2. Thus, blending requires the use of extended databases to be the most efficient at the cost of motion capture time and storage capacities.

Timewarping is another method used to generate walking motion at various speeds. Unlike motion blending, timewarping requires only one input motion to generate a wide range of new speed modified motions. It consists in shortening or lengthening the duration of a motion clip by reducing or increasing the number of frames accordingly. When the number of frames increases, the gait cycle is longer and thus the walking speed is reduced. To obtain the missing skeleton positions at the new frames, interpolations are performed between the two existing frames. Increasing walking speed is performed by deleting intermediate frames. While this technique presents the benefit of needing only one input motion, the speed modification of the motion only affects the overall speed of the animation. More specifically, only the gait duration and thus the step frequency of the motion is modified which leads to motions that can be perceived as unnatural by

observers as the biomechanical properties of human walking are not taken into account. In particular, Prazak et al. (2010) showed that speeding motions up is easily detected by observers, while slowing it down is less easily perceived. In regards to the benefits and disadvantages of these two methods, our leg animation technique presents the advantage of requiring only one input motion to generate various biomechanically-based motions. However, it remains to determine if the produced motions from our framework are visually valid. To investigate this issue, we present the framework of a perceptual study in which we propose to compare the naturalness of motion captured walking motions with walking motions generated with our method, motion blending and timewarping. In particular we use the three different methods to generate motions at given various speeds that match the walking speed of a number of motion captured ground truth examples. As our method solely generates lower body motions without taking into account the upper body motion in its current state, we propose to focus on the lower body motion only to validate this first part. This last point is further discussed in Section 5.4. The perceptual experiment have however not been conducted yet at the time of writing this manuscript, and this section therefore only presents the general proposed framework and discusses potential issues and expected results.

### 5.3.1 Methods

#### Stimuli preparation

For the purpose of the experiment, we used the motions that we captured and presented in Section 5.2. We computed the walking speed of each motion and use them for the generation of all the new motions. For example when modifying a comfort walking speed motion to a slow walking speed motion for a given actor, the exact walking speed of the recorded slow motion will be used as a target speed value. For timewarping and our *poulaine* motion editing techniques we generated 6 different motions for each actor, 3 speed-up motions and 3 slow-down motions. The three speed-up motions were: slow speed (from very slow motion), comfort speed (from slow motion), fast speed (from comfort motion). The 3 slow-down motions were fast speed (from very fast motion), comfort speed (from fast motion), slow speed (from comfort motion). To avoid any artefact, we decided to edit the motions from the closest motions for each of the three different editing techniques.

## Poulaine methods

To edit the motions using our *poulaine* method, we first computed the *poulaines* at slow, comfort and fast speeds for each actor and retrieved the 5 control points described in Section 5.1. Then, using the relationship between the characteristic points position and walking speed (see linear regression description in Section 5.1), we modified the positions of each control points to fit the desired walking speed. Then we used Hermite interpolation with the new control points to obtain the *poulaine* corresponding to the trajectory at the desired speed. Finally, the knee and hip joint positions and orientations are computed at each frame using inverse kinematics and the corresponding ankle position from the *poulaine* for each frame. Finally, as we only modified the motion of the lower body but not the overall speed of our character, we apply a transformation to the root of the motion to modify its forward speed to match the target speed.

## Motion Blending

Motion Blending required to generate only three different motions (for three different speeds) per actor. All of the three motions require 2 different motions to blend between. For example, the comfort speed motion was generated by blending the slow and fast speed motions, and to weight the different motions accordingly to generate a motion whose speed matches the original comfort motion speed. Similarly, we generated the slow motion by blending the comfort and very slow motions, and we generated the fast motion by blending the comfort and very fast motions together. In total we had 3 different motions (slow, comfort and fast speeds) which will be used for both the speed-up and slow-down conditions.

## Timewarping

Timewarping was produced in two steps. First, we calculated the theoretical number of frames required to obtain the desired speed while keeping the same framerate. In particular we have:

$$v = d/t \tag{5.4}$$

with  $v$  the speed of the motion,  $d$  the distance traveled by the root and  $t$  the total gait cycle time. We also have:

$$t = N/f \tag{5.5}$$

with  $N$  the total number of frames and  $f$  the framerate of the motion. As a result, we finally have:

$$v = d.f/N \quad (5.6)$$

Thus, modifying the number of frames while maintaining the framerate and the root distance allows us to modify the walking speed of the character. Then, we computed the new timewarped frames by linearly interpolating the existing frames using Spherical Linear Interpolation of Rotations (SLERP) on local quaternion, so as to insert more/fewer frames at relevant times. Because the framerate stays the same it will effectively stretch or condense the animation in time.

We generated a total of 24 motions (6 motions for each of the 4 actors).

### 5.3.2 Task

In the proposed experiment, participants will be presented with two walking motions side by side and asked to select the most natural in their opinion in a two alternative forced choice design. The two walking motions presented on screen will always consist in one walking motion reconstructed with one of the three methods (Blending, Timewarping, Poulaine-based), as well as a captured walking motion at the corresponding speed. As our method only modifies lower body motion, we decided to choose a viewpoint focusing the visual attention of the user to the legs, as seen in Figure 5.7. Motions will be randomly presented on the left or right part of the screen. No information about the naturalness of the motion will be given to the participants. Stimuli will be presented to the participants for a maximum of 10 seconds, after which they will be forced to choose the motion they consider to be the most realistic in their opinion, using the left and right keys on the keyboard accordingly. A total of 48 stimuli will be presented to the participants (4 Actors x 3 Speeds x 2 SlowDown/SpeedUp x 2 Side).

## 5.4 Discussion and Future Works

### 5.4.1 Poulaine as a tool to edit motion

In this chapter, we evaluated the possibility to use the *poulaine*, or ankle cyclogram, as a tool to control and edit walking animations of virtual characters. In particular we proposed a framework to generate walking animations based on our analysis of how the

shape of the *poulaine* is influenced by different demographic and kinematic parameters (Section 5.1). The generation of the walking animations is performed following different steps. First the *poulaine* is represented as a set of control points which serve as interpolation nodes to reconstruct the *poulaine* curve. The choice of number of control points and the interpolation to use was based on two evaluations, one objective and one subjective (Section 5.2). The objective evaluation consisted in comparing mathematically the reconstructed *poulaines* and the ground truth, while the subjective evaluation consisted in a user study in which we also compared the reconstructed *poulaines* and the corresponding ground truth animations. When the *poulaine* is reconstructed with the chosen parameters, an inverse kinematics algorithm compute the corresponding knee and hip positions and orientations to synthesize the walking animation.

To evaluate our synthesized walking animations, we propose a perceptual experiment in which we compare our method with current technique to synthesize walking motions at specific walking speeds (Section 5.3).

### 5.4.2 Future Works

Our first objective is to perform the perceptual study presented in Section 5.3 in order to evaluate the relevance of using our *poulaine*-based method to synthesize walking animations at a specific speed in comparison with other traditional approaches.

Second, a future perspective to investigate is the generation of the upper body motion. We focused on lower body motion as we found in Chapter 4 that legs are the body part where participants focus most of their attention on when rating the naturalness of walking motions. However, creating walking motions with varied characteristics is especially valuable in the context of creating diverse virtual crowds, in which case other body parts are equally or more important. In particular, Hoyet et al. (2016) showed that adding shoulder motions on a virtual character enhances the visual quality of large scale scenarios while keeping a low computational cost. McDonnell et al. (2009) demonstrated that observers fixed significantly more the torso and head when trying to spot two individuals sharing the same motion in a group of walking characters. Thus, upper body motion variety seems to help reducing the feeling of uniformity in crowd scenarios. Our next goal is therefore to investigate how to modify arm swing motion similarly to our *poulaine* technique. By looking into the literature, arm swing motion is a partially passive motion but muscle activity is also required to drive this motion (Meyns et al. 2013; Goudriaan et al. 2014). Other studies in human locomotion focused on highlighting the correlation between arm swing,

walking speed (Romkes and Bracht-Schweizer 2017) and demographic features (Hejrati et al. 2016). The latter demonstrated that walking speed, height and slope were the major factors influencing arm swing during locomotion and proposed a mathematical framework to analyze arm swing. They demonstrated that using a Fourier series, it was possible to fit a curve that approximates the shoulder angle cycle. We could adapt their framework to propose a method to generate arm swing at various walking speeds and actors' height. To evaluate the appealing and naturalness of our synthesized arm swing motions, we will conduce perceptual experiment investigating different paradigm.



# COLLABORATION

## Contents

---

<b>6.1</b>	<b>Perception of motion variation in large-scale crowds . . . . .</b>	<b>104</b>
6.1.1	Methods . . . . .	105
6.1.2	Results . . . . .	108
6.1.3	Discussion . . . . .	109
<b>6.2</b>	<b>Walking speed and trunk sway: studying the effects of gait features on collision avoidance . . . . .</b>	<b>112</b>
6.2.1	Methods . . . . .	114
6.2.2	Results and Discussion . . . . .	118
<b>6.3</b>	<b>Conclusion . . . . .</b>	<b>121</b>

---

This chapter presents two studies on which I collaborated during my PhD. While I was not the main investigator for these studies, they bring interesting insights to the topic explored in this manuscript.

In the different previous chapters, we investigated the use of biomechanical parameters to generate more diverse and realistic human motions. We found that participants were relying on different biomechanical properties to evaluate the naturalness of the motion. This is important, as it gives insights on the use of new animation control parameters to bring variety in crowd scenarios. However, little is known about the minimum amount of motion variety to add to enhance the feeling of variety in such scenarios. In the Section 6.1, we investigate this issue in the context of large-scale crowd scenario. In this study, I was mainly involved in the different research discussions as well as in the supervision of the master student who conducted the study.

Additionally, interacting with a single virtual character is also a common task in entertaining applications with users controlling a main character or interacting with a Non Player Character (NPC). Thus, understanding how observers behave in presence of a virtual character with different specific characteristics is valuable to improve the

involvement of the user. In Section 6.2, we explore the effect of different gait features on the collision avoidance strategy of walkers. In particular we investigate the effects of the walking speed and of the degree of trunk sway on the collision avoidance strategy of young adults. For this collaboration, I was mainly involved in the experimental aspects by designing and performing the experiment.

## 6.1 Perception of motion variation in large-scale crowds

As seen in Chapter 2, it is important to bring variety to improve the overall realism of applications which deal with large groups of characters. However, when dealing with a very high number of characters, introducing variety can increase the cost of the application, both in terms of acquisition and runtime performance. Thus, understanding the amount and location of variety to add for a crowd to be realistic is a valuable information when trying to design efficient crowd applications. Such a question has been investigated in scenarios involving a maximum of 24 characters, where Pražák and O’Sullivan (2011) demonstrated that three unique motions were enough to make a crowd look varied. However, it is not certain that these results could be extrapolated to large-scale crowd scenarios, as having more clones present on screen can lead to easier detection. Our goal is therefore to investigate the perception of motion clones in such large-scale crowds (up to 1000 characters). As it is extremely difficult to acquire unique motions for every single individual in such cases, we are also interested in this study to explore the use of statistics-based methods for creating motion variations to increase the visual variety and realism of these scenarios. To achieve these objectives, we designed an experiment in which we investigated the perception of motion clones in large-scale crowds (from 250 to 1000 characters). Users were presented with video pairs of virtual crowds in which characters were either animated with a unique synthesized motion, or with a subset of these motions. We hypothesized that:

- H1.** The lack of variety would be more easily noticed by viewers in virtual crowds using fewer numbers of unique motions (i.e., using more motion clones)
- H2.** The lack of variety would be less noticed as the number of unique motions increased until a threshold, above which participants would not perceive differences anymore.
- H3.** The small minimum number of unique motions (3) identified in previous studies would not hold for larger crowds, as motion clones would be significantly more

present and easy to spot (McDonnell et al. 2008), and that some, potentially more distinctive, motion clones might also be more easily identified (Hoyet et al. 2013).

### 6.1.1 Methods

#### Stimuli Generation

We implemented the statistics-based approach of Ma et al. (2010) to create sufficient statistical variations for this study. In short, the approach generates motions in two steps. First, for each desired motion to be generated, a set of *style parameters* is specified. For example the desired output motion is one of a female of average height, walking at average speed. From this set of input style parameters, *variation parameters* are computed for each limb using a Bayesian Network (BN). In the second step, both style and variation parameters are fed into a Kriging model that computes interpolation weights used to interpolate database motions together such as to reflect the characteristics given by the style and variation parameters in the resulting interpolated motion. In addition to these two fundamental steps, we applied a pre-processing step to normalize input motions in time and space using timewarping to synchronise footsteps (Witkin and Popovic 1995), as well as to retarget them to a common skeleton (Kulpa et al. 2005). A post-processing step was also necessary to inverse the process and retarget the motions to either a male or female character, as well as to correct potential artifacts (e.g., footsliding). Both the BN and the Kriging model parameters are learnt from a database of existing motions. For this study, we used 156 motions captured from 43 actors (20F, 23M) walking at their comfort speed. These animations were provided by the authors of (Hoyet et al. 2013), some of which were previously used for other experiments as well (Zibrek et al. 2020). Their animations were obtained using a 19-camera Vicon optical tracking system, with 67 markers positioned on each actor’s body. We used 4 walking clips per actor, and although motions from the same actor are naturally less varied they still provide additional variety for the model to interpolate from.

As mentioned above, the motion synthesis model is driven by a set of style parameters, for which we chose to include actor gender and step length. Gender was chosen as a way to keep generated motions coherent with character appearance. Step length was chosen as it allowed further control on the distribution of walking speeds. It is to note that additional parameters could have been chosen to reflect physical features of the characters, like morphology or age. However, because we lacked sufficiently varied motions according to

those additional parameters, we chose to limit the complexity of the model to the two aforementioned parameters.

Finally, we created 1000 motions using the described synthesis method, equally distributed in gender, and with step lengths randomly sampled from a normal distribution matching the database motions ( $\mu = 0.77\text{m}$ ,  $\sigma = 0.06\text{m}$ ). Variation parameters were then chosen randomly by the BN to synthesize each motion.

For the purpose of the experiment, we then created videos of crowd animations. As we were interested in the relative number of motion variations presented to participants, additionally to gold standard videos displaying a unique motion for each character we created videos with 5 different levels of *Variation Ratio*: 1:2, 1:5, 1:10, 1:25, 1. 1:N means that one motion is used for N different characters, while the 1 value corresponds to a single motion used for all the characters of the same gender. It is important to mention that in all cases, the number of varied motions is split between male and female characters, as there are an equal number of each. For the specific 1 value, we chose to use an absolute number rather than a ratio in order to represent the worse case scenario where only one motion example per gender is used to animate a whole virtual crowd. Also, as using distinctive motions might highly affect the perception of motion clones in such a case, we chose to focus on the most difficult situation where none of the motions are visually outstanding. For the 1 condition, we therefore randomly used one of the three least distinctive male and female captured motions from (Hoyet et al. 2013), as it would be normal to be demanding about the animations available when only a few examples are required.

As we were also interested in exploring whether the number of characters present in the crowd might affect the perception of motion clones, we generated crowd scenes with 3 different *Crowd Size*, displaying in total 250, 500 or 1000 characters as seen in Figure 6.1. The higher the size of the crowd, the larger the set of different motions used, and the more varied the scene might seem. However, the scene is also more cluttered, which might make it more difficult to spot clones. The exact number of motions used for each condition is summarized in Table 6.1. Because appearance clones are more easily noticed than motion clones (McDonnell et al. 2008), sufficiently varied character appearances should be used to avoid disturbing the perception of motion variety. We used a set of 40 characters (20 males and 20 females), each featuring 6 texture variations for a total of 240 appearance variations.

Table 6.1: Number of unique motions used for each condition. \*number of male and female motions were counter-balanced over the experiment in these conditions.

		Crowd Size		
		250	500	1000
<b>Gold Standard</b>	<b>1:1</b>	125F,125M	250F,250M	500F,500M
<b>Variation Ratio</b>	<b>1:2</b>	63F,62M*	125F,125M	250F,250M
	<b>1:5</b>	25F,25M	50F,50M	100F,100M
	<b>1:10</b>	13F,12M*	25F,25M	50F,50M
	<b>1:25</b>	5F,5M	10F,10M	20F,20M
	<b>1</b>	1F,1M	1F,1M	1F,1M

### Task

Participants were presented with video pairs of crowd scenes. On one video of each pair, every character was animated with a unique synthesized motion (Gold Standard), while on the other video the characters' animations were a subset of these motions. The participants' task was to select the video which they considered had the most unique animations. To generate these videos, we used the 1000 synthetic motions created using the approach detailed above. In total, participants were presented with 45 video-pair comparisons:  $5 \text{ Variation Ratio} \times 3 \text{ Crowd Size} \times 3 \text{ Repetitions}$ . In each condition, the video was presented side-by-side with the golden standard video using a unique synthetic motion for each character. The golden standard video was randomly presented on the left or right side of the screen, and the presentation order of the conditions was also randomized. Both videos in a pair played simultaneously, were 28s long, and could be visualised twice. After that, we asked participants to select the scenario they perceived to have the most unique animations, if they had not already provided their answer. The study was conducted online, however videos were all loaded locally before the experiment began, ensuring that they would play without interruption at the original bitrate and resolution. They were presented to participants in full screen.

### Participants

Twenty participants (12F, 8M; age: mean=29.9, min=18, max=66) performed the experiment online. They were recruited using internal mailing lists, and did not receive any compensation. They were all naive to the purpose of the experiment, and gave their informed consent prior to the experiment. Data collected from participants were fully



Figure 6.1: Examples of virtual crowds stimuli: (left) 250 characters animated with 1 female and 1 male motion, (centre) 500 characters animated with 25 female and 25 male synthetic motions, (right) 1000 characters animated with 500 female and 500 male synthetic motions (i.e. a unique motion per character).

anonymised. The study conformed to the declaration of Helsinki.

## Data Collection and Analysis

For each participant, we computed the percentage of correct answers for each *Variation Ratio* and *Crowd Size* condition across the three repetitions, where an answer was considered to be correct if participants selected the gold standard video (i.e., displaying a unique synthetic motion for each character). We assessed normality of the data using a Shapiro-Wilk normality test. As residuals were found to be non-normally distributed, and the participants' answers are discrete, we transformed this non-parametric data using the Aligned Rank Transform procedure (Wobbrock et al. 2011). With this method, the data is aligned and ranked before being tested with a traditional Analysis of Variance (ANOVA) to analyze interaction effects. We then performed a two-way Repeated Measures ANOVA with within-subject factors *Variation Ratio* (1:2, 1:5, 1:10, 1:25, 1) and *Crowd Size* (250, 500, 1000) on the percentage of participants' correct answers. Bonferroni post-hoc comparisons were performed when a significant main or interaction effect was found. We also performed a t-test on the percentage of correct answers against the 50% chance level threshold, to assess whether participants' answers were significantly above chance.

### 6.1.2 Results

Because of the cost of animating human crowds, as well as budget constraints, a small number of motions is often used to animate a larger set of characters. In this study, we were interested in whether results from previous studies exploring how many unique motions are required for motion clones to be imperceptible in small groups of characters

(up to 24 characters) would remain valid for large-scale crowds (up to 1000 characters).

We found a main effect of the *Variation Ratio* ( $F_{4,266} = 2.6804, p = 0.0321$ ) on the percentage of correct answers, suggesting that some amounts of motion variations were distinguished significantly more often by participants (Figure 6.2). However, post-hoc analysis showed a significant difference only between 1 and 1:10 *Variation ratios* ( $p = 0.0318$ ), which does not provide any meaningful insight, and is likely due to chance. No other comparisons were significant, even with the 1:25 ratio that is in between 1 and 1:10. No other main or interaction effect was found: crowd size did not influence the detection of the gold standard, regardless of the amount of variation present in the other scene.

As mentioned previously, we also conducted single t-tests to assess whether the percentage of correct answers was significantly above the 50% chance level threshold. Results showed that only the crowds animated with a single motion per gender (1 *Variation Ratio*) were recognised often enough by participants to be significantly above the 50% chance level ( $F = 2.213882, p = 0.0392$ ). For higher *Variation Ratios*, participants did not chose the gold standard frequently enough to conclude of a significant perceptual difference between the two scenes. These results suggest that viewers can identify crowds animated with 2 motions only (one per gender), and that introducing a few more varied animations is perceptually equivalent to animating each character with its own unique motion.

### 6.1.3 Discussion

First, the results showed that 2 unique motions (one male and one female) were enough to animate virtual crowds that are perceived as significantly different from the gold standard, invalidating our **H1** and **H2** hypotheses. For all the other conditions, participants could not distinguish between the condition and the gold standard in terms of unique motions, invalidating our **H3** hypothesis. Even for the condition involving only one unique female and male motion, the accuracy was very low (60%) indicating that the task was maybe too difficult. This was confirmed by the post experimental ratings of the experiments where 18 out of 20 participants rated the task Difficult to Very Difficult. However, the accuracy rate in our study is in the same range than the same condition in previous work involving small-scale crowds ( $\approx 63\%$  accuracy (Pražák et al. 2011)). In both their and our study, participants performed similarly regardless of the difference in the number of characters or in the fact that we deliberately chose to use validated non-distinctive motions in our experiment (as it would be normal to be demanding about animation quality when using only a few examples). Thus our results suggest that for large-scale crowds,

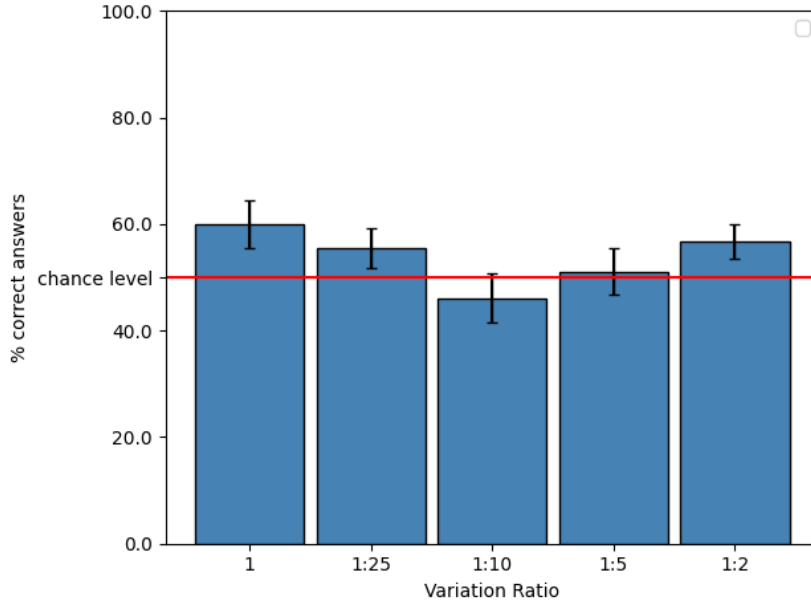


Figure 6.2: Percentage of correct answers for each *Variation Ratio*. The chance level (*red*) indicates a statistically random choice. Error bars represent the Standard Error of the Mean.

a very low number of unique motions could be considered to reduce the uniformity in the animations of the characters. It should also be mentioned that the small participant sample size in this ( $N=20$ ) and their ( $N=12$ ) study might not reflect the accuracy of the general population, and that a larger number of participants might provide stronger evidence that differences in accuracy for higher *Variation Ratios* in our results are not due to chance.

As mentioned above, crowds using variation ratios of one motion for 25 characters or less could not be significantly discriminated from the gold standard by the participants. This result invalidates the **H3** hypothesis that previous result of using only 3 motions might not hold for large-scale crowds, as this condition corresponded to using between 10 and 40 motions in our experiment depending on the crowd size. The results of this experiment also show that the perception of motion clones do not seem to be influenced by the size of the crowd presented to the participants, as mentioned in previous work too (Pražák et al. 2011). This combined results indicate that the perception of large-scale crowds and small-scale ones follow the same mechanism and therefore, crowd size does not influence the performance of detecting clones.

The low accuracy of the participants response in this study might be explained by how

the variation was introduced in the crowd. For such large-scale scenarios, it is impossible to solely rely on motion capture data to animate each virtual character. Thus in this study, a state-of-the art approach was used to synthesize unique motion variations. While most of these motions were validated to show a relative range of distinctiveness (Hoyet et al. 2013), their choice and number might have influenced how varied the synthetic motions were. For instance, if synthetic motions seemed too similar to viewers, the various crowd stimuli might have been perceived as uniform, and differences in variation levels more difficult to spot. As the synthesis method is based on motion blending, the number of actors and motion clips in the database, as well as their overall distinctiveness, set a limit to the truly varied combinations that can be obtained. Another crucial parameter is the quality and naturalness of synthetic motions, as artifacts and unnatural gaits could draw viewers' attention and help them spot multiple characters exhibiting the same behaviour. While the Bayesian Network ensured that variation parameters of all body parts comparatively matched the database motions, we noticed while visualizing individual synthetic motions some small visual artifacts where the motion of a body part seemed to be mismatched with the rest of the body. This supports our motivation to use other methods to automatically generate varied animations that are not only more faithful to the biomechanics of the human motion but also configurable according to each virtual character specificities in terms of morphology, age or gender as we described in Chapters 3, 4 and 5.

Another possibility to improve the variety is to modify the speed distributions of the characters. Varying speeds means that quicker characters try to pass slower ones, creating clutters and gaps. For the purpose of this experiment, this could have introduced a diversion of the attention of viewers from the actual character motions but in a less theoretical approach, varying speed might be a factor to improve the feeling of variety. However, methods dealing with speed modifications often require an extensive database or do not respect biomechanical rules and are easily spotted by observers (Pražák et al. 2010). Thus, the use of the approach proposed in Chapter 5 to automatically modify the speed of a motion, while keeping the naturalness of the human motion, could be extremely valuable in such a context for creating variety at low cost.

Finally, although 3 different sets of speeds and trajectories were used for each crowd size, they all shared the same flow direction. An unidirectional flow direction also means that characters are mostly seen from the same angle, and coupled with the choice of a low field of view the stimuli presented almost all characters from the same angle. However, observing characters from a remote viewpoint might have diminished participants' ability

to perceive the details of their motion and prevented them from spotting motion clones. Exploring the effect of point of view on crowd perception therefore seems to be important for future work, especially as it was recently found that an eye-level point of view seems to enable users to more accurately perceive visual artifacts in character trajectories, possibly because of being closer to the one we are used to experience as humans (Cabrero Daniel et al. 2021).

## 6.2 Walking speed and trunk sway: studying the effects of gait features on collision avoidance

While displaying characters that look varied and unique is important for the realism of crowd animations, another important aspect is to be able to display characters that present natural ways of interacting with other characters. In this context, creating characters that naturally avoid collisions with others while navigating in a virtual environment is extensively explored by the community. As for the biomechanical parameters we explored in previous chapters, individual characteristics might also influence how we interact with another person in such a situation. For instance, we might leave more space with someone who looks agitated or fragile.

Avoiding obstacles is an everyday task. For example, when walking to a specific location, humans need to step around obstacles or other humans on their trajectory. To successfully avoid an obstacle, walkers use visual information about their surrounding, their self-motion and their positioning within the environment (Lee 1980). Previous collision avoidance studies focused on interactions with inanimate objects (Cinelli and Patla 2008; Gérin-Lajoie et al. 2008; Gérin-Lajoie et al. 2005; Vallis and McFadyen 2003) or between pair of humans walking (Olivier et al. 2013). These studies focus on collision avoidance strategies, showing for example that walkers preserve a personal space with an elliptic shape when walking (Gérin-Lajoie et al. 2005), or that both walkers contribute to avoid the collision but the walker passing second contributes more to the avoidance. Some other studies have considered the effects of situational factors (e.g., the angle (Basili et al. 2013)) or individual factors (e.g., the effect of age (Rapos et al. 2019; Rapos et al. 2021)). Studying such an interaction is complex in real conditions and Virtual Reality (VR) offers in that context very interesting experimental opportunities. Indeed, VR enables to replicate real life scenarios in a controlled and precise framework. In particular, it enables to replay a specific task an infinite number of time while controlling precisely

some relevant features and experimental factors (e.g., virtual human's motion), which is valuable for research experiments. In particular, such experimental designs enable to investigate different gait features that could affect one's avoidance strategy as gait is a rich source of information as perceptual studies demonstrated that observers were able to easily recognize one's age (Montepare and Zebrowitz-McArthur 1988), gender (Kozlowski and Cutting 1977), identity (Cutting and Kozlowski 1977) or emotion (Atkinson et al. 2004) from their motion. Although some studies investigated the collision avoidance strategy in VR of participants when presented with virtual walkers presenting different gait features (e.g., limb movements (Fiset et al. 2020)), it is still unclear to what extent gait-based information is used to avoid the collision with an approaching person. Walking speed and degree of trunk sway are two self-selected gait-based information immediately available to the visual system and are gait features varying among humans. Particularly, elderly people are associated with lower walking speeds (Bohannon 1997), and higher degree of trunk sway (Lee et al. 2014). These gait characteristics may influence collision avoidance strategies, as Rapos et al. (2021) demonstrated that young adults do not interact in the same manner when crossing with another young adult or an elderly person. In this study, people were able to see each other when crossing and thus could determine the age of their counterpart which may influence their crossing strategy. Thus, there is still a lack of understanding about how individuals avoid each others when presented with different quantities of walking speed and degree of trunk sway without age cues.

In this section, we thus investigate the impact of person-specific walking speed and degree of trunk sway on the spatio-temporal patterns of collision avoidance behaviours. We therefore designed a pedestrian crossing task in a VR scenario, where a virtual character with different walking speeds and degrees of trunk sway was approaching the participant, who was asked to walk to a target point while avoiding the virtual character. The objective was to determine the spatio-temporal patterns of collision avoidance behaviours used during the collision avoidance task at specific walking speed and degree of trunk sway values.

We thus hypothesized that:

- **H1:** Participants will demonstrate a larger clearance at crossing when the speed of the virtual character is slower.
- **H2:** Participants will demonstrate a larger clearance at crossing when the sway of the virtual character is higher.

### 6.2.1 Methods

In this study, we want to adapt the degree of trunk sway and the walking speed of the virtual character according to participants own characteristics. To obtain each participant's speed and sway, we first asked them to walk along a 18-meter pathway towards a goal located at the end of the pathway, in both a real and virtual environment.

#### Blend Tree

Prior to the experiment, we recorded the walking motions of 1 male and 1 female actor using a Xsens IMU-based motion capture system at a sampling rate of 120 Hz. We asked each actor to walk at various walking speeds from very low to very fast. For each walking speed, we also asked the actors to walk while maintaining the trunk as straight as possible or inversely exaggerating their trunk sway to obtain a wide range of trunk sways. We then designed a blend tree to control the walking animations of the virtual character similarly to the blend trees presented in Chapter 3 and Chapter 4, with a main blend tree using walking speed as control parameter, and controlling 3 different sub-blend trees using degree of trunk sway as control parameter. This enables us to generate walking animations with the desired walking speed and trunk sway, depending on each participant's characteristics.

#### Stimuli preparation

We first instructed participants to walk along an unobstructed path toward the goal in the real-world environment three times at a freely chosen selected speed. We then asked participants to walk the same pathway three additional times in the virtual environment while we recorded their comfort walking speed and trunk sway. Walking speed was obtained by tracking markers with a 24-camera Qualisys motion tracking system sampled at 120Hz. The markers were fixed on a FOVE head-mounted display (70Hz, 100-degree field of view) that we used to immerse the participants in the virtual environment. Trunk sway was measured using a Xsens MTw Awinda inertial measuring unit sampled at 240 Hz and placed on the sternum of the participant (see Figure 6.3a). We averaged the participants comfort walking speed and trunk sway of the virtual environment trials. The average comfort walking speed and trunk sway were used to normalize the walking characteristics of the virtual character that will be used as a stimuli in the experiment. Using the Blend Tree presented in 6.2.1, the virtual character was animated with a walking motion at

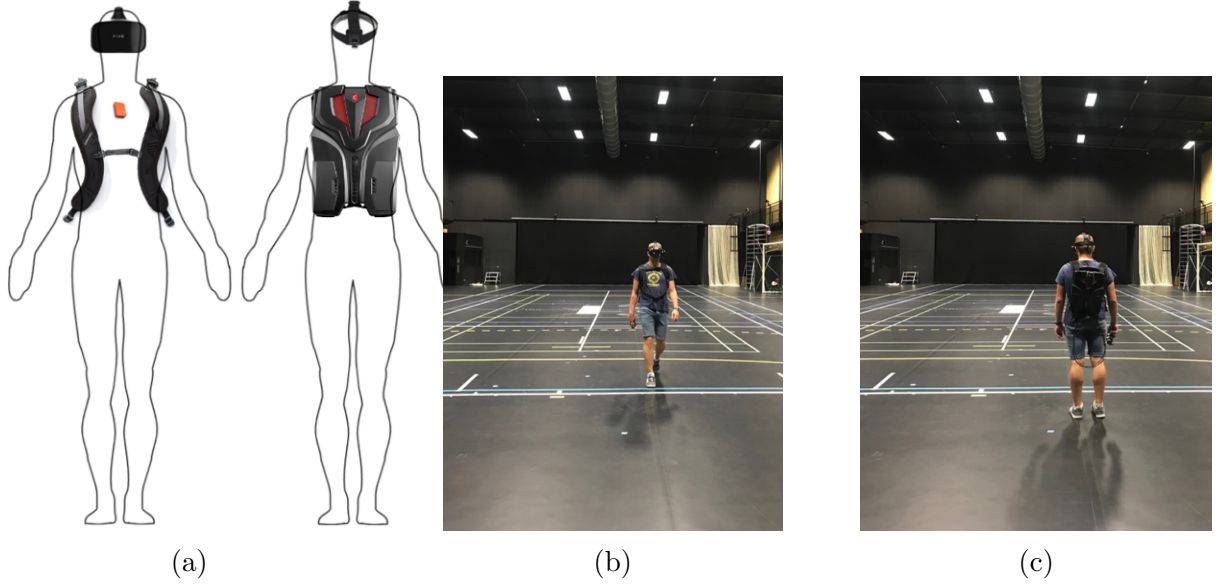


Figure 6.3: Experimental set-up for our pedestrian crossing experiment. (a) Participant equipment set-up with a FOVE head-mounted display, Xsens inertial measuring unit, laptop backpack. (b) and (c): Experimental layout in real world

one of three predetermined speeds, slow ( $0.8 \times$  participant's walking speed), normal ( $1.0 \times$  participant's walking speed) and fast ( $1.5 \times$  participant's walking speed) and three predetermined degrees of trunk sway amplitudes: small ( $0 \times$  participant's sway), normal ( $1.0 \times$  participant's sway) and large ( $2.0 \times$  participant sway). We treated each speed and sway conditions separately meaning that for each speed condition, the sway of the virtual character always remained "normal" while in the sway conditions, the speed of the virtual character was always set to "normal", resulting in a total of 5 experimental conditions. To avoid any character appearance effects, we selected one female and one male virtual character from the Microsoft Rocketbox library and participants interacted with both of them. Therefore, there were a total of 30 experimental trials consisting of 5 conditions repeated 3 times, while interacting with two different virtual characters ( $5 \text{ conditions} \times 2 \text{ virtual characters} \times 3 \text{ repetitions}$ ). Trials were randomized during the experiment, such that the virtual character would change direction towards the left or right to mitigate any habituation or assumptions regarding the avoidance paradigm.

### Task

Participants performed 5 familiarization trials to avoid any learning effect. During these 5 familiarization trials, they interacted with a virtual character whose walking speed

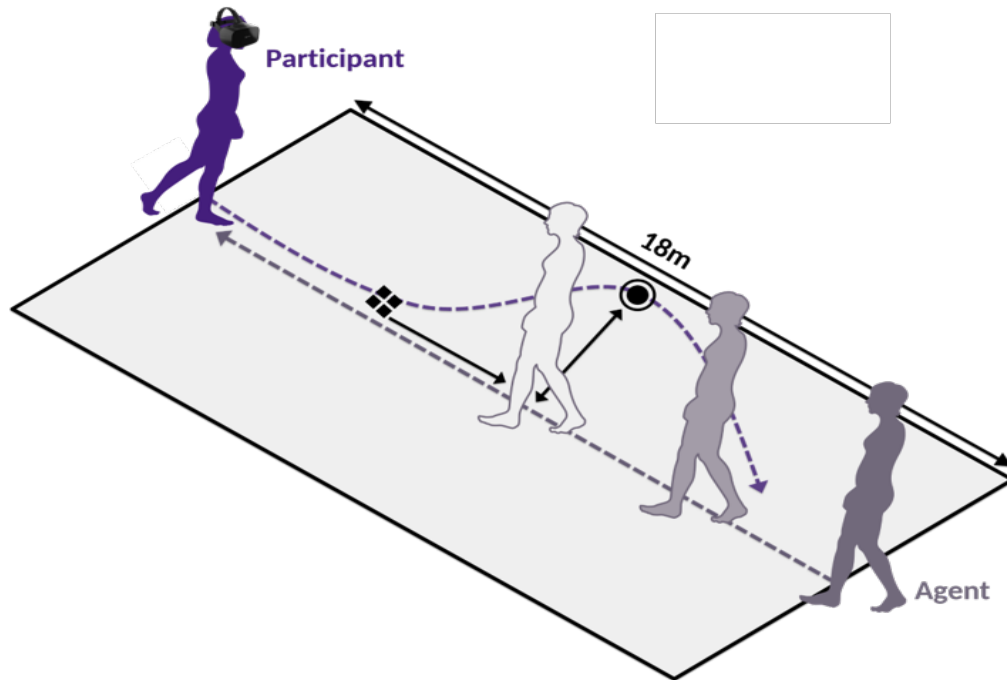


Figure 6.4: Initial path deviation (square) and clearance distance (dot) investigated in our pedestrian crossing experiment

and degree of trunk sway was normalized to the participant. During the avoidance task, a virtual character with one of the five condition characteristics approached the participant along a 180-degree colliding pathway. Participants were told to avoid the virtual character and walk toward a target point, with no specific instruction or restriction given to them about their walking speed and trajectory selection. Before seeing the approaching virtual character, participants passed through a set of virtual sliding doors to enable them to reach steady-state walking speeds before initiating an avoidance behaviour. In order to maintain a constant time-to-contact (TTC, i.e; the time that remains until a collision between two walkers occurs if the collision course and speed difference are maintained (Minderhoud and Bovy 2001)) throughout all experimental trials, the starting position of the virtual character was modified based on the virtual character's walking speed such that the theoretical point of collision always occurred at the same time after being able to see the virtual character. Finally at the end of the experiment, participants were asked to complete 3 unobstructed walking trials of the same virtual pathway to evaluate pre and post experimental differences. In total, 54 walking trials (real and virtual), were completed by all participants. During the experience, participants could ask for a break at any moment. At the end of the experience, a feedback was given on the objectives and

the purpose of the experiment.

## **Participants**

Twenty-one participants (10 females, 11 males, age: mean =  $24.5 \pm 2.3$  years) with no disability or neurological disorder that could affect their locomotion were recruited for the experiment. All participants volunteered to the experiment, and were recruited using internal mailing lists. Participants did not receive any compensation. They were all naive to the purpose of the experiment, and gave written and informed consent. Testing procedures were approved by the Wilfrid Laurier University Research Ethics Board, and the Inria Research Ethics Board (COERLE).

## **Data Collected**

Seven reflective markers were positioned on the head-mounted display and tracked using the motion tracking system at 60Hz. From the tracked markers, participants' position, walking trajectory and velocity were calculated. Anterior-Posterior (A-P) and Medio-lateral (M-L) positions of the participant relative to the virtual character were computed from the position of the head-mounted display. Data was filtered using a second order low-pass Butterworth filter, with a cut-off frequency of 0.5 Hz to remove any high frequency stepping oscillations. Participants initial path deviation (point at which someone begins their avoidance away from a straight walking trajectory and begins to deviate laterally) was calculated using the M-L position of the head-mounted display and by tracking backwards in time from when the participant's M-L center of mass had deviated laterally by 20 cm, until the moment when the M-L center of mass deviation is only 2 cm from a straight walking path (see Figure 6.4) signifying the instant in time when the participant was on a new trajectory (Gérin-Lajoie et al. 2007). The walking speed of each participant was computed using the time derivative of the HMD A-P positional data. Participants' walking speed, prior to the initial path deviation was defined as the approach velocity. Mean freely chosen walking speed of each participant was calculated during the unobstructed trials in real-world before and after the exposure to the virtual environment. Recording of the walking pre-exposure and post-exposure to the virtual environment allowed us to compare if any changes in walking velocity occurred due to acclimatization of virtual reality exposure. From participants positions, we also computed the Medial-Lateral Clearance which corresponds to the absolute M-L distance between the participant and the virtual character as they passed one another (see Figure 6.4) at time of contact. This variable

was estimated using the M-L position of the HMD relative to the virtual character's M-L center of mass position at the time of contact. In addition to these metrics we also computed the avoidance rate which is the velocity at which participants move laterally out of the virtual character's trajectory. We computed it as the difference of M-L positions of the HMD between the start of the avoidance and the time of contact divided by the time required by the participant to travel this distance.

## Analysis

Statistical analyses were performed within SPSS software (Version 24.0, IBM Corp., North Castle, NY). Data was assessed for normality, sphericity, and homogeneity of variances. Where appropriate, the Greenhouse-Geisser correction was applied for any violations of sphericity. In order to determine if manipulation of trunk sway influenced participant's avoidance behaviours, we ran two separate repeated measures ANOVAs to test for main and interaction effects on participants' theoretical time to contact and M-L clearance at time of contact. There were two within-subject factors of virtual character trunk sway (x0, x1, x2), and sex with respect to virtual character (matched or unmatched). Additionally, to determine if manipulation of virtual character walking speed influenced participant's avoidance behaviours, we ran two separate repeated measures analysis of variance (ANOVA) to test for main and interaction effects on participants' theoretical time to contact and M-L clearance at time of contact. There were two within-subject factors of virtual character walking speed (x0.8m/s, x1.0, or x1.5m/s) and sex with respect to virtual character (matched or unmatched).

### 6.2.2 Results and Discussion

Figure 6.5 presents the temporal results of the experiment. We found that at faster walking speed, participants initiate significantly later their avoidance strategy. However, we did not find a significant effect of trunk sway on TTC.

Figure 6.6 and Figure 6.7 present the spatial results of the experiment. We found that neither walking speed or degree of trunk sway influenced Clearance at time of crossing, which invalidates **H1** and **H2** hypotheses.

Theses results suggest that individuals might use a point in space instead of temporal information to determine when to initiate a deviation in their trajectory, which is in agreement with the literature (Cinelli and Patla 2007; Cinelli and Patla 2008). Overall,

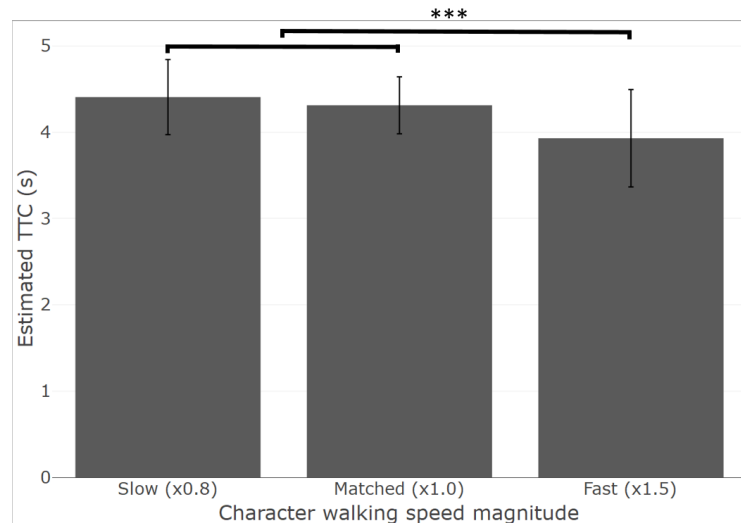


Figure 6.5: Effect of walking speed condition on Time to contact when participants initiate deviation of their trajectory.

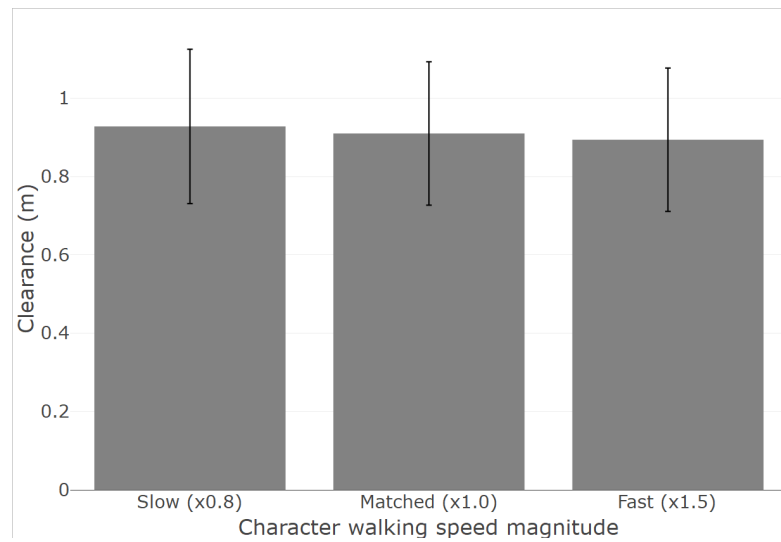


Figure 6.6: Effect of walking speed on clearance distance.

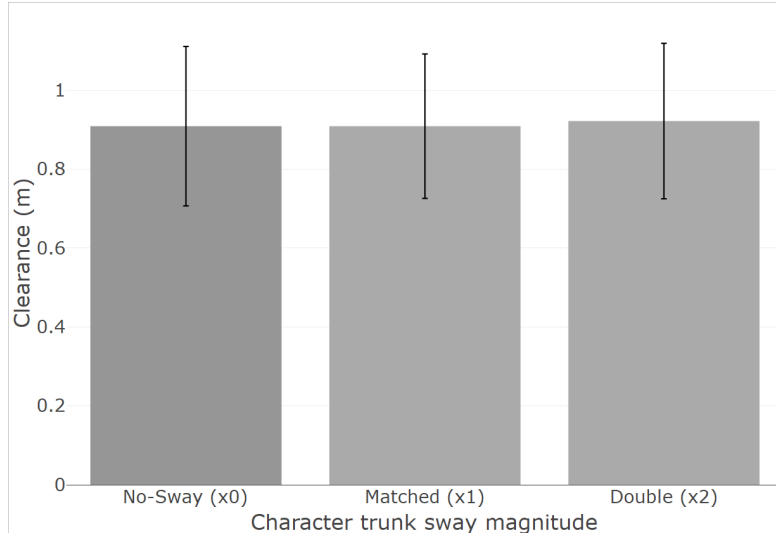


Figure 6.7: Effect of degree of trunk sway conditions on clearance distance.

we found no influence of the degree of trunk sway on TTC, Medio-Lateral clearance and avoidance rate of our participants.

In this study we tried to negate the effect of appearance by selecting two young virtual characters. The smaller walking speed and higher degree of trunk sway are associated with a more elderly gait pattern (Bohannon 1997; Lee et al. 2014) and thus, we expected participants to present different collision avoidance strategies when presented with the lower speed or higher sway conditions. Indeed, in a collision avoidance task, young adults contribute more to collision avoidance behaviours than elderly adults (Rapos et al. 2021). As we did not find a significant effect of the degree of trunk sway on both TTC and clearance distance, we propose different explanations to this results. First, we think that the sway magnitude range was too narrow to observe any effect, as they were relative to each participant’s own sway. Second, we did not combine the conditions resulting in lower walking speeds conditions to be only combined with a normal degree of trunk sway and higher degrees of trunk sway to be only combined with a normal walking speed. However, it is possible that combining both lower speed and high degree of trunk sway is required for recognizing a more vulnerable gait pattern. Finally, we decided to use two young virtual characters in our experiment, which may lead to participants taking less care in avoiding them, even when they displayed features that would correspond to a vulnerable gait for characters with an elderly appearance. Future works will thus focus on exploring wider magnitudes of trunk sway and the use of different character representations, including older adults, to better understand the relative effects of both motion and appearance on

collision avoidance.

## 6.3 Conclusion

In this chapter, we presented two distinct collaborative works that are linked to this thesis. First, we investigated the perception of different levels of motion variations in large-scale virtual human crowds (with the number of characters ranging from 250 to 1000). We conducted a perceptual experiment in which we evaluated observers' accuracy at distinguishing crowds populated with characters having their own unique motion and crowds presenting motion clones. Even for low levels of motion variety (1 motion for 25 characters) participants had difficulties in discriminating between the more and less varied crowds. In this study, only crowds animated with 2 motions (1 per gender) tended to be noticed as less varied by viewers. The results suggest that, as in smaller-scale crowd scenarios, motion variations in crowds are quite subtle and motion clones difficult to spot thus requiring to better understand motion variety to better control such variety in crowds.

Second, we investigated the effects of walking speed and degree of trunk sway on collision avoidance behaviours in young adults. We conducted a collision avoidance experiment in which participants had to move toward a target location while avoiding a virtual character presenting different walking speeds and degrees of trunk sway. Participants were immersed in a virtual environment enabling us to control accurately the degree of trunk sway and walking speed of the character presented to them. The results suggest that participants might use a point in space to initiate avoidance rather than temporal information and that the degree of trunk sway was not affecting collision avoidance. However, these results need to be confirmed by further experiments exploring in more details wider ranges of gait features in combination with additional factors such as the appearance of the virtual characters.

In the context of this thesis, these two studies help us to have a better understanding of motion variety in the context of computer animation. In particular, the first study provides guidelines on the maximum number of motion clones that can be used in large-scale crowds to keep a varied crowd in the users' perspective. On the other hand, the second study highlights how personalising gait features and appearance of virtual characters for interactive entertaining applications might influence our interactions with these characters.



# CONCLUSION

---

## Contents

---

<b>7.1 From Analysis and Perception of Walking Animation to Animation Guidelines . . . . .</b>	<b>123</b>
7.1.1 Experimental Results . . . . .	123
7.1.2 Recommendations to edit walking motions . . . . .	125
<b>7.2 Future works . . . . .</b>	<b>126</b>
7.2.1 Short-Term Perspectives . . . . .	126
7.2.2 Long-Term Perspectives . . . . .	129

---

In this thesis, we were interested in exploring novel ways of generating walking animations that are adapted to specific characteristics of a virtual character, while being natural to an observer's eye, in order to create virtual character motions that look visually varied when populating virtual environments. To this end, we investigated the use of biomechanical parameters presenting inter-individual differences to edit and control walking animations that respect the biomechanics of human walking motion. While these parameters have been widely studied in the biomechanical literature, they were not or little studied in the context of the perception of virtual characters' motions. We therefore proposed perceptual experiments to investigate the relevance of two different kinematic variables for computer animation applications, namely the Walk Ratio and the *Poulaine*.

## 7.1 From Analysis and Perception of Walking Animation to Animation Guidelines

### 7.1.1 Experimental Results

The first contribution of this thesis was to investigate how the Walk Ratio (the ratio between step length and step frequency naturally selected by a walker) was perceived when

---

walking motions were applied on virtual characters. This parameter was well studied in the biomechanical literature and was shown to present differences related to gender, age and morphology while being invariant across speeds for a given individual. These attributes are very interesting in the context of computer animation as theoretically, it provides a simple controller to edit the walking motions from a virtual character to another, or from one speed to another while keeping its naturalness. However, this parameter has not been used in Computer Animation, thus we decided to investigate the ability of viewers to perceive the natural Walk Ratio of individuals on virtual characters. To this end, we performed a perceptual experiment in which we asked participants to modify the step frequency (thus the Walk Ratio) of walking characters until they found the most natural motion in their opinion. We found that the participants estimated motions with a significantly lower Walk Ratio for the female characters than the male characters and that for a given character, the Walk Ratio was perceived invariant across speeds, as predicted by the literature (Sekiya et al. 1997). As it was the first experiment investigating the perception of this parameter of human walking, the actor pool of this experiment was rather low and we could not ensure that the gender differences found in the first contribution were not simply due to morphological differences between the male and female characters. Furthermore, small differences were found between the perceived Walk Ratio of the characters and the natural Walk Ratio of the corresponding actors.

In a second contribution, we thus decided to further explore the respective effects of gender and morphology on the perception of the Walk Ratio, while simultaneously investigating if using Virtual Reality (VR) was associated with a better recognition of the natural Walk Ratio of observers. We therefore performed another perceptual study in which we quadrupled the number of actor motions presented to the participants, depicting a wider range of morphological characteristics. We also decided to present the motions on characters matching the gender of the actors we captured the motions from, as well as on characters which did not match the gender of the original actors in order to explore whether perceived Walk Ratio differences were more influenced by motion or character appearance. We enabled participants to modify the motions of virtual characters through their step frequency until they found it the most natural. We conducted the experiment using two display setups, one using a traditional screen as in the first contribution, and one using a VR Head Mounted Display. As in the first contribution we found gender differences between male and female participants which disappeared when normalising data by the actors' height. We found no effect of weight or the display condition. Furthermore, we

---

found no difference when the motions were displayed on the gender-matched or gender-mismatched virtual characters which indicate that height is more important than gender when estimating this biomechanical parameter of human walking. However, we also found that the actors with a higher comfort walking speed were associated with higher Walk Ratios. Therefore, for characters sharing the same height and gender, we recommend to use a higher WR for characters with a higher comfort walking speed characteristic.

In our third contribution, we presented a method to generate and edit walking motions using the *poulaine*, i.e. the representation of the ankle trajectory as seen in the hip reference frame. We first analysed how the shape of the *poulaine*, and more specifically the position of different control points, is influenced by different individual characteristics (age, gender, height, weight and walking speed). We found that height and walking speed were the most important predictors of the shape of the *poulaine* and that walking speed was the main predictor when data were normalized by the stature of the actors. We then proposed a method using the *poulaine* to reconstruct walking motions by interpolating between different numbers of control points using 3 different interpolation techniques. Though a perceptual study we validated our reconstruction framework, and chose the interpolation technique and number of control points to use to best reconstruct the *poulaine*. After validation of the reconstruction, we propose a method to edit the *poulaine* based on the results of our initial analysis to generate walking motions adapted to a target walking speed. The next step will consist in evaluating the effectiveness of our editing tool by comparing it with other state-of-art methods. We will perform a perceptual study in which we will compare our technique with Motion Blending and Time Warping to generate walking motions at various speeds to validate its use in computer animation.

### 7.1.2 Recommendations to edit walking motions

From the results of our different contributions, we propose different guidelines to edit the motions of virtual characters. As explained in our first contribution, the natural perceived Walk Ratio (the step length to step frequency ratio) of a virtual character is estimated similarly at different walking speeds. This would suggest than when modifying the walking speed of an individual, animators should modify both step length and step frequency to keep the ratio invariant and thus preserve the naturalness of the character's motion as well as an individual's characteristics. As explained in Chapter 5, commonly used speed editing techniques do not account for such parameters, leading to motions that can appear unnatural to the observer's eye or requiring more input motions to achieve

---

the same results as our proposed method.

Another possibility to edit motions through the use of the Walk Ratio is to keep the speed constant but vary the characteristics of the virtual character. In our second contribution, we found that differences of height between female and male actors were the origin of Walk Ratio’s disparities. Thus, when adapting the motion from a tall actor to a smaller one, the Walk Ratio should be decreased accordingly by reducing the step length while increasing the step frequency to keep a constant walking speed. These methods are still difficult to realise efficiently using traditional animation techniques, while the *poulaine*-based method enables us to control directly both step length and thus indirectly the Walk Ratio, which seems promising for motion editing.

## 7.2 Future works

### 7.2.1 Short-Term Perspectives

In our last contribution we explored different individual characteristics (age, height, weight, gender) that could have a potential impact on one’s gait characteristics and in particular on the *poulaine*, i.e. the trajectory of the ankle as seen in the hip reference frame. Our first results demonstrated that walking speed and height were the most relevant features to explain the variations in different characteristic points of the *poulaine*. However, we used a database with a range of age (from 19 to 67 years old) and Body Mass index (BMI) (between 20 and 25 kg/m<sup>2</sup>) which are not associated with different gait patterns in the biomechanical literature, even though individual gait differences have been observed on similar ranges (Hoyet et al. 2013). Several studies trying to predict gait characteristics on such metrics already pointed out the relevance of age, gender, BMI and walking speed on 3D kinematics and kinetics with the latter having more importance as a predictor (Chehab et al. 2017; Moissenet et al. 2019). In particular, Chehab et al. (2017) showed that 69 of the 78 gait features chosen in their study were associated with variations in walking speed, while only 28 of the 78 gait features were correlated with at least one demographic feature (e.g., age, gender, height and weight). Moissenet et al. (2019) built upon these results to predict lower limb sagittal gait kinematics. Using walking speed, gender, age and BMI they could predict the angle and timing of 21 key points divided between the hip, knee and ankle. Similarly to Chehab’s results, they found that walking speed was the predictor influencing the most gait kinematics. Similarly, in our

---

second contribution we found that walking speed had an effect on the perception of the Walk Ratio. This suggests that walking speed might contribute more than demographic features in both the action of walking but also in its perception. However, similarly to the literature, our range of actors used in the second contribution was limited in terms of weight and age disparity. Future studies should focus on exploring further the perception of walking animations under demographic features that are more associated with different gait patterns. In particular, investigating the perception of elderly walking motions or motions from people with extreme values of BMI will be our main focus in a close future, as it could provide us more insights on how to use the Walk Ratio and the *poulaine* to generate walking animations with these specific patterns.

In our second contribution, we tried to investigate if the perception of the Walk Ratio was affected by the appearance of the virtual character. More specifically, we applied motions of our original actors on virtual characters whose gender was matching or not the actor's one. We found that participants chose the same natural Walk Ratio regardless of the character on which the motion was displayed. This potentially suggests that appearance has less effects than motion when evaluating such biomechanical parameters of walking motion applied on virtual character. However, previous perceptual studies showed that when trying to recognize the sex of a walker when motion is applied on different models, participants tend to rate female walks on male models ambiguous and conversely (McDonnell et al. 2009a). Thus, a distinction must be made between a task that aims at evaluating naturalness and a task that aims at determining specific features from gait. Other related studies evaluated the effect of appearance of virtual characters on different metrics. For example, Iachini et al. (2016) investigated how comfort and reachability distances were affected by the appearance of a virtual character interacting with a user. They found that both distances were moderated by gender (reduction with females; expansion with males) and age (expansion with adults; reduction with children) and that appearance may influence more these distances than motion (Zibrek et al. 2020). In a close future, we therefore want to have a better understanding of the relative effects of appearance and motion when rating naturalness. While several studies investigated the effect of sex (McDonnell et al. 2009a; Zibrek et al. 2015), there is for instance a lack of knowledge on the perception of motions with mismatched age or morphology. Understanding the mechanisms ruling the perception of such features could raise opportunities in creating more varied crowds.

In our last contribution, we mainly focused on editing lower-body motions. More specif-

---

ically we highlighted the impact of walking speed on the shape of the *poulaine*. However, we have not taken into account the upper body during these analyses. The main reason for exploring lower body editing first was that we found that observers are more focused on the legs when estimating the Walk Ratio of a walking virtual character. However in entertaining applications, observers may be more attentive to the upper body part as we would with real life counterparts. In a clone detection task, McDonnell et al. (2009) demonstrated that head and torso attract the majority of first fixations and were the body parts the most attended to. Based on their results, they provide guidelines to increase the overall variety of a crowd by playing with the appearance of virtual characters through the use of accessories, top textures and facial textures. To bring variety at the motion level and “hide” pedestrian collisions, Hoyet et al. (2016) added shoulder motion to a virtual character walking against a unidirectional crowd flow. They showed that the additional shoulder motion increases significantly the visual quality of a crowd animation. These results indicate that adding upper body variety would improve the overall naturalness of the crowd scenario. Thus, our next focus is to extend our motion editing approach to upper body modifications. As explained in our third contribution, studies in human motion demonstrated that arm swing is partially a passive motion but muscle activity is also required to drive this motion (Meyns et al. 2013; Goudriaan et al. 2014). As for lower limb motion, researchers investigated several factors that could affect arm swing. In particular, walking speed was found to have a strong effect on upper body kinematics (Romkes and Bracht-Schweizer 2017), while Hejrati et al. (2016) mathematically modeled arm swing for different walking speeds, slopes and demographic conditions. Our next step is to build upon this work to synthesize arm swing motion in respect to walking speed, as our *poulaine* method does for lower limb motion. Having the ability to animate independently the upper and lower body of a virtual character provides additional tools for animators to generate varied crowds, but it raises additional research questions. Indeed very crowded scenarios may lead to characters occluding each others and we can wonder if in such scenarios, animating partially occluded characters would produce a similar level of variety while reducing computational time. In particular, further work should focus on determining how to generate variations in the most efficient manner by investigating the relative contribution of upper and lower body in the perception of variety in crowd scenarios, where the variety should be added and how much is required to keep a high level of variation.

---

## 7.2.2 Long-Term Perspectives

In this thesis, we investigate the question of motion variety by focusing on the walking motion solely. However, humans perform various actions on a daily basis. Thus, a simple way to add motion variety to populated environments is to use different common types of motions to virtual characters such as conversing, sitting, picking up a phone or running. Among all these motions we are interested in running as, similarly to walking, running is a cyclic motion widely studied in the biomechanical community while presenting a different dynamic. In the context of computer animation, running motions are usually obtained from motion capture data. Many techniques developed to synthesize or edit walking animations from motion capture data have been adapted to running motions. In particular, statistical (Bruderlin and Williams 1995; Bodenheimer et al. 1999), learning (Bruderlin and Calvert 1996), motion blending (Park et al. 2002), physics-based (Rajagopal et al. 2016) or constraints-based (Ren et al. 2010) techniques have been adapted to running examples. However, these methods present the same limitations presented in Chapter 2, thus adapting running animations to specific virtual characteristics would require to understand how this motion is influenced by various anthropometric parameters (e.g., age, gender, height, weight), gait features (e.g., running speed) and individual technique (e.g., running performance). In particular, the sport science community demonstrated that age (Fukuchi and Duarte 2008; DeVita et al. 2016), gender (Chumanov et al. 2008; Sinclair et al. 2012) or experience in running (Knechtle et al. 2012; Buchheit and Mendez-Villanueva 2014) were associated with different running patterns. From its cyclic nature, other studies proposed to use the *poulaine* representation, presented in Chapter 5, to analyse further the technique of athletes when running (Natta and Réga 2000; Decker et al. 2007). In the future, we want to adapt the methodology of our approach presented in Chapter 5 to running motions. More specifically, we want to propose a method to automatically synthesize running animations from the *poulaine* and the characteristics of an actor running and validate them through user studies. Another advantage of using the *poulaine* for this other motion is to be able to control better the transition between the walking and running animations. Currently, computer graphics techniques blend between a walking and a running animation to generate an intermediate animation. However, the transition between walking and running is more complex than just averaging the two motions (Segers et al. 2006; Segers et al. 2013). Thus, investigating a common kinematic variable would help in synthesizing walking-to-running and running-to-walking transitions.

In this thesis, we investigate primarily the question of variety in individual characters

---

as well as crowd scenarios where the user is external to the environment using a typical screen viewpoint, as they would be when watching a movie or playing a video game. However, the definition and investigation of motion variety must be reevaluated when the context of the application is modified. In particular the development of Virtual Reality (VR) applications propose to the user a more immersive experience than traditional screens. It is more and more used in various applications such as education, healthcare, sports performance or art in which the user is able to interact with virtual characters, in a vast amount of scenarios. Some scenarios require to populate the environment with virtual characters that behave with a purpose, like a normal human would do, to keep the user involved in the environment. For example, exploring the street of a city requires to depict liveliness as a normal street would, with characters owning their unique appearance and performing everyday actions, e.g., chatting or walking. However, similarly to crowd scenarios on screens, populating such environments with an increasing number of unique virtual characters is resource-consuming. Saving resources is even more critical for VR applications as the involvement and feeling of immersion of the user can be nullified if the application does not run smoothly. Thus, current VR applications rely on duplicating virtual characters' appearance and motion to reduce their complexity. Even though such designs still enable researchers to produce experimental designs that preserve the ecological validity of a given task (Berton et al. 2020), the potential of designing more and more realistic crowded environments remains limited by the current technological capabilities. Thus, investigating how to enhance the realism by adding variations using as few resources as possible is also a key research topic in VR. One of our next objective is therefore to investigate how to add variations in VR applications from a perceptual point of view. A starting point in this domain would be to investigate, similarly to topics investigated in screen applications (McDonnell et al. 2008), the relative importance of appearance and motion of characters to increase variety. This would help greatly in selecting the most salient parameters to modify in order to enhance realism. Other studies would focus on evaluating variations added in the virtual environments, for example in our second contribution, we barely scratched the surface of perception of motion in VR. While there is an extensive amount of studies dealing with the perception of self motion in VR, little is known on the perception of characters' motions in such environments. The main difference between VR and screen applications is the immersion of the user. In a crowd context, users will be interacting with characters in a first person viewpoint in VR and in a more global viewpoint for screens. Thus, in VR participants may focus more on

---

the closest characters when trying to perform a specific perceptual task, while participants using traditional display may have a more global view of the crowd. This could help in choosing where to put variations in VR applications in a sort of level of detail fashion. For instance, variations would not be required when participants try to interact with a character hidden by others, while they would become necessary when a character arrives in the perceptual range of the user.

Overall, the contributions presented in this PhD manuscript open the way to novel ways of creating individual-specific motion variations to further explore such questions in the future.



# RÉSUMÉ LONG EN FRANÇAIS

---

## Context

La marche est l'une des tâches les plus courantes effectuées par les humains, pour se déplacer d'un lieu à un autre. Elle ne nécessite pas de compétences ou d'équipements spécifiques et constitue une activité sportive quotidienne pour des milliards de personnes. Chaque jour, nous sommes entourés de personnes qui marchent vers leur destination, parfois seuls, parfois en groupe. Bien qu'il soit courant de voir des groupes de personnes marchant à la même vitesse afin de pouvoir discuter ensemble à la sortie d'un stade après un événement sportif ou d'une manifestation sportive, il est peu probable qu'ils partagent les mêmes attributs morphologiques et surtout si le nombre de marcheurs dans le groupe augmente.

Dans de tels scénarios, les personnes partagent un chemin et un objectif communs un bref instant mais avec leurs propres caractéristiques (par exemple, l'âge, la morphologie, l'humeur) et leurs habitudes de marche. Bien que nous soyons habitués à cette diversité dans les scénarios de foule de la vie réelle, les applications ludiques ont encore du mal à reproduire la complexité des foules ambulantes. Idéalement, chaque personnage dans un jeu vidéo ou un film devrait avoir l'air et se comporter comme une entité unique lorsqu'il est présenté sur un écran pour produire des personnages réalistes et donc des scènes vivantes et spectaculaires. Pour reproduire cette diversité, la technique la plus simple utilisée par l'industrie cinématographique consiste à recruter et à coordonner autant de figurants que nécessaire pour une scène spécifique, en comptant de quelques individus à des centaines de milliers, ce qui constitue un cauchemar logistique pour les réalisateurs. Par exemple, plus de 300 000 figurants ont été recrutés pour le tournage d'une scène de moins de 4 minutes dans le film Gandhi (1982). Avec l'amélioration des capacités graphiques des ordinateurs, les foules peuvent désormais être recréées dans un environnement virtuel pour être incluses après coup lors de la post-production, améliorant indéniablement la capacité à créer rapidement des foules de base. Cependant, la diversité et l'aspect attrayant de la foule sont souvent perdus car l'individualisation de l'apparence, du mouvement et du comportement de chaque personnage virtuel requiert d'énormes ressources et n'est donc



Figure 7.1: Foule typique du jeu vidéo NBA 2k14. Les points jaunes correspondent aux clones d'apparence, c'est-à-dire aux personnages ayant des vêtements et un modèle de personnage similaires. Les points bleus correspondent aux clones de mouvement, c'est-à-dire aux personnages partageant la même animation. Les points verts indiquent les clones qui partagent à la fois le mouvement et l'apparence.

souvent pas réalisable. Une stratégie courante pour réduire ces coûts est de dupliquer les actifs de quelques personnages (en termes d'apparence, pose, mouvement) à de multiples personnages à l'écran, ce qui conduit à une certaine uniformité dans la foule et diminue son naturel, comme le montre la Figure 7.1. Dans cette figure, on peut clairement observer que certains personnages portent la même tenue et ont le même modèle facial, on les appelle des clones d'apparence (points jaunes dans la Figure 7.1). Nous pouvons également distinguer des personnages ayant une apparence différente mais partageant une pose similaire à cette image, ce qui suggère qu'ils ont la même animation et donc le même mouvement dans l'application. Ces clones sont appelés "clones de mouvement" (points bleus dans la Figure 7.1). Nous pouvons également observé des clones partageant à la fois la même apparence et le même mouvement (points verts dans la Figure 7.1). Tous ces clones confèrent à une application une certaine uniformité qui réduit drastiquement l'implication de l'utilisateur. Pour réduire ce sentiment d'uniformité, le plus simple est de jouer avec les clones d'apparence et de mouvement et de contrôler précisément leur nombre et leur position sur la scène pour éviter que les observateurs ne les repèrent (McDonnell et al. 2008).

D'autres effets gênants peuvent se produire lors de la duplication d'un mouvement sur

---

un personnage virtuel dont les propriétés morphologiques ou individuelles sont très différentes. Par exemple, animer une femme âgée et fragile avec le mouvement d'un très jeune individu musclé pourrait sembler étrange aux yeux de l'observateur. Ainsi, il existe un besoin évident pour les applications animées virtuellement de réduire leur uniformité tout en conservant des comportements cohérents. En particulier, ces applications nécessitent d'ajouter des variations entre les personnages, en termes d'apparence et de mouvement. Bien que certaines lignes directrices aient été fournies pour augmenter la variation des personnages par l'apparence (McDonnell et al. 2008; McDonnell et al. 2009c), la variation de mouvement nécessite toujours une quantité énorme de travail artistique manuel. Les techniques axées sur l'édition des mouvements existants pour générer des variations de ces mouvements sont donc précieuses pour la communauté de l'infographie. Cependant, ces techniques existantes se concentrent principalement sur les variations statistiques des mouvements qui manquent souvent de contrôle précis sur les mouvements générés, ce qui peut entraîner une incongruité entre l'apparence et le mouvement des personnages.

Dans cette thèse, nous nous intéressons à l'exploration de la manière d'apporter des variations aux humains virtuels à travers les mouvements. Plus précisément, nous nous concentrerons sur la marche, l'un des mouvements les plus couramment utilisés dans les applications interactives. Nous allons étudier comment générer facilement des mouvements de marche qui ne sont pas seulement réalistes, mais aussi adaptés aux caractéristiques spécifiques des personnages afin de peupler les environnements virtuels de personnages qui affichent des mouvements différents et congruents avec leurs caractéristiques individuelles (par exemple, l'âge, le sexe, la taille). Plus précisément, nous voulons utiliser les paramètres biomécaniques des mouvements de la marche humaine pour contrôler et éditer des animations de marche. L'utilisation des paramètres biomécaniques de la marche humaine nous semble prometteuse car ils représentent souvent des caractéristiques simples (par exemple, la longueur des pas, la fréquence des pas, la vitesse de marche) à régler pour les animateurs et ont été largement étudiés dans la littérature sur le mouvement humain.

## Notre approche

Cette thèse traite de la création de mouvements de marche spécifiques aux caractéristiques d'un individu afin de créer des mouvements de marche de personnages virtuels qui ont l'air visuellement variés. Cependant, l'ajout de variations est une tâche difficile et soulève de nombreuses questions. Qu'est-ce que la variation ? Quelle quantité de vari-

---

ation est nécessaire ? Où doit-on placer la variation ? La variation est-elle perçue par les observateurs ? Les variations apportent-elles des mouvements non naturels perçus par les observateurs ? Pour répondre à ces questions, il faut comprendre et étudier différents sujets de recherche. Tout d’abord, nous voulons comprendre ce qui rend le mouvement d’une personne unique, en fonction de diverses caractéristiques démographiques et anthropométriques (par exemple, l’âge, le sexe, la taille, le poids). Le domaine de recherche qui traite de ces questions est appelé **Analyse du mouvement**. Plus précisément, nous nous concentrons sur les paramètres invariants du mouvement de la marche humaine et sur sa modélisation pour proposer des méthodes permettant de générer et de modifier des mouvements de marche adaptés à un ensemble spécifique de caractéristiques d’acteurs de manière automatique et rapide. En particulier, dans cette thèse, nous adaptons des techniques de **Synthèse de mouvement** existantes (Motion Blending, Cinématique Inverse) avec nos résultats d’analyse de mouvement pour synthétiser des animations de marche adaptées aux caractéristiques des acteurs. Bien que la combinaison de l’analyse et de la synthèse de mouvement nous permette de générer des animations de marche qui sont fidèles aux lois biomécaniques du mouvement, elles ne nous assurent pas que les observateurs perçoivent ces animations comme plus attrayantes ou plus réalistes que celles générées par les techniques traditionnelles de synthèse de mouvement. On peut également se demander quelles sont les caractéristiques des acteurs ou les parties du corps qui influencent le plus la variété d’une scène avec des personnages qui marchent. D’autres questions se posent également, par exemple en ce qui concerne la quantité de variations nécessaires pour rompre l’uniformité d’une scène, ou sur l’importance relative de l’apparence et du mouvement sur la variété d’une scène. Pour répondre à ces questions, nous proposons des méthodes dérivées du domaine de la **Perception**. En particulier, nous réalisons des études d’utilisateurs où des participants sont invités à évaluer le réalisme d’animations de marche contrôlées par différents paramètres.

Dans cette thèse, nous proposons donc une approche combinant ces trois thèmes de recherche (voir Figure 7.2). En particulier, nous nous appuyons sur l’analyse du mouvement de la marche d’un point de vue biomécanique pour proposer des cadres de travail permettant d’éditer des animations de marche. Nous évaluons ensuite la pertinence de nos cadres de travail par le biais d’études d’utilisateurs dans lesquelles nous examinons en détail comment utiliser efficacement ces cadres pour l’animation de personnages.

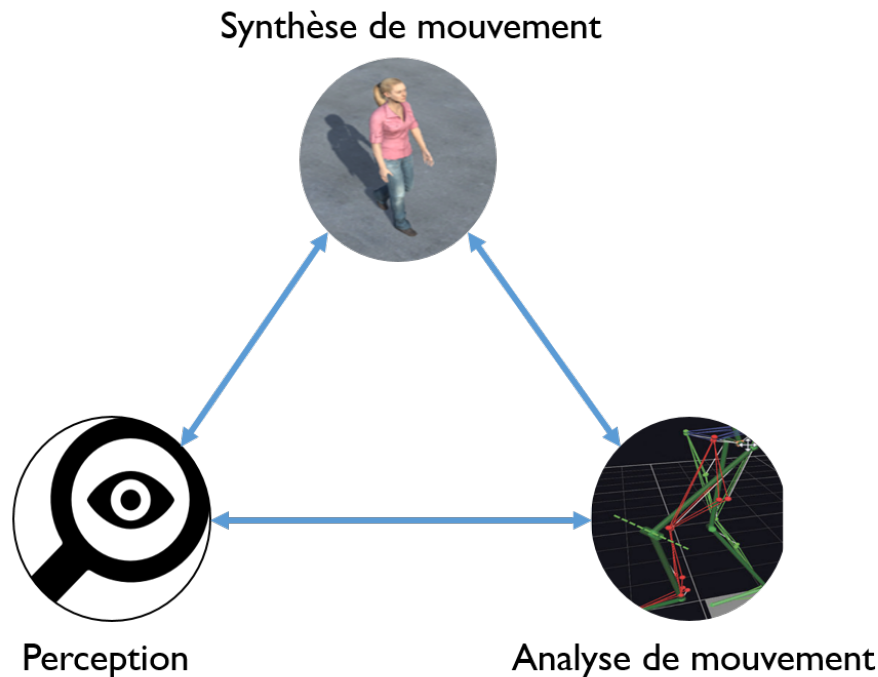


Figure 7.2: Dans notre approche, nous combinons l'analyse du mouvement et la perception pour générer de nouvelles animations pour les personnages virtuels.

## Contributions

Cette thèse présente trois contributions principales basées sur trois études expérimentales différentes. Dans la première contribution (Chapitre 3), nous explorons la pertinence d'une variable cinématique de la marche humaine pour générer et éditer des animations de marche. Cette variable, nommée ratio de marche, est définie comme le rapport entre la longueur et la fréquence des pas et a été étudiée dans la littérature biomécanique. Elle n'a cependant jamais été utilisée en animation, alors qu'elle présente des caractéristiques potentiellement intéressantes pour le contrôle des animations de la marche humaine, telles que l'invariance des vitesses pour un individu donné, ainsi que des différences liées au sexe, à la morphologie et à l'âge. Pour étudier sa pertinence dans en animation, nous avons réalisé une expérience perceptive dans laquelle les participants devaient modifier le mouvement de marche de personnages virtuels en jouant sur la fréquence de leurs pas, qui modifie le ratio de marche. En particulier, on leur a présenté des mouvements à différentes combinaisons de longueur et de fréquence de pas tout en gardant une vitesse de marche constante. Comme la vitesse est le produit de la longueur et de la fréquence des pas,

---

modifier l'un de ces paramètres revenait à modifier automatiquement l'autre pour conserver la même vitesse. Les participants pouvaient modifier la fréquence des pas et donc la longueur des pas des mouvements affichés jusqu'à ce qu'ils choisissent la combinaison de ces deux paramètres la plus naturelle à leurs yeux. Le rapport longueur de pas par rapport à la fréquence des pas de la combinaison choisie était le ratio de marche estimé pour chaque personnage virtuel présenté aux participants, que nous avons comparé au ratio de marche naturel (capturé) des acteurs correspondants dont les mouvements ont été utilisés dans notre expérience. Nos résultats ont montré que les observateurs estiment les ratios de marche qui sont dans la fourchette des ratios de marche naturels décrits dans la littérature biomécanique. Nous avons trouvé des différences entre les sexes dans la perception des ratios de marche, mais une invariance entre les vitesses pour un acteur donné, ce qui est également en accord avec la littérature biomécanique sur le ratio de marche. Ce travail a été accepté et présenté à l'ACM Symposium on Applied Perception 2020 (Niay et al. 2020).

Cette première contribution a été la première étude à explorer l'utilisation potentielle du ratio de marche comme paramètre de control d'animations de marche. Pour cette raison, cette première étude était limitée à un petit nombre d'acteurs (4). Nous avons donc décidé d'étendre cette contribution dans une deuxième expérience (Chapitre 4), afin d'évaluer si nos résultats pouvaient être généralisés à un plus grand nombre d'acteurs (16). Cela nous a permis d'explorer d'autres facteurs qui pourraient affecter la perception du ratio de marche, comme le sexe de l'acteur, sa taille, son poids ou sa vitesse de marche. Dans cette contribution, nous avons également exploré d'autres facteurs perceptifs en affichant les mouvements sur un modèle de personnage dont le sexe est assorti et sur un modèle de personnage dont le sexe n'est pas assorti afin d'explorer si la perception du ratio de marche était plus influencée par le mouvement ou l'apparence, ainsi qu'en utilisant à la fois la réalité virtuelle (RV) et un écran traditionnel pour présenter les stimuli aux participants. Nos résultats ont montré que le sexe, la taille et les vitesses de marche individuelles étaient associés à un ratio de marche significativement différent. Nous n'avons pas non plus trouvé d'effet de l'apparence du personnage (modèle adapté ou non au sexe) et de la condition d'affichage (écran ou RV) sur le ratio de marche perçu. La première et la deuxième contribution démontrent que le ratio de marche a le potentiel d'être utilisé pour contrôler et éditer les animations de marche des personnages virtuels tout en garantissant le caractère naturel des mouvements de marche.

Dans une troisième contribution (Chapitre 5), nous avons étudié l'utilisation de la

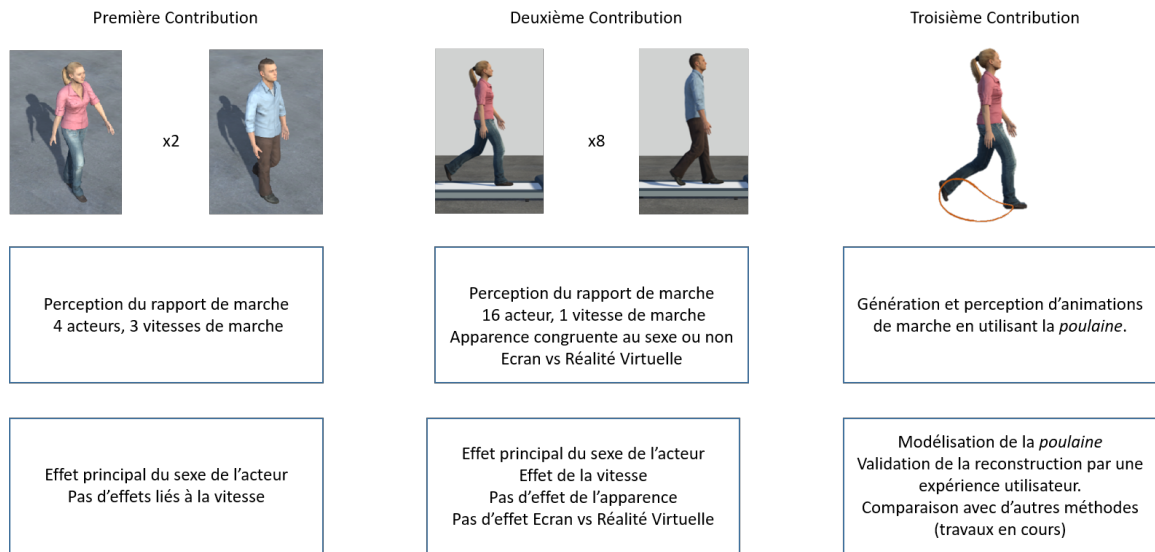


Figure 7.3: Résumé des principales contributions de cette thèse

poulaine, une autre variable cinématique caractérisant la locomotion humaine, pour éditer des animations de la marche des jambes. La poulaine correspond à la trajectoire de la cheville vue dans le référentiel de la hanche. Nous proposons une approche en trois étapes. Tout d'abord, nous analysons comment la forme de la poulaine est influencée par les caractéristiques individuelles. Ensuite, nous proposons une méthode de reconstruction du mouvement du bas du corps basée sur la poulaine et nous fournissons des moyens de modifier la poulaine selon les caractéristiques individuelles souhaitées. Enfin, nous proposons un cadre pour évaluer notre méthode de reconstruction à travers une expérience perceptuelle dans laquelle nous comparons notre méthode avec d'autres approches de l'état de l'art. La Figure 7.3 présente un résumé des différentes contributions.

Enfin, le Chapitre 6 présente plusieurs travaux collaboratifs dans lesquels j'ai été impliqué au cours de mon doctorat, sur des sujets liés à la variété dans l'animation de foule et l'évitement des collisions avec les piétons. Plus précisément, nous avons étudié le nombre de mouvements nécessaires pour obtenir une foule qui semble plus variée qu'une foule animée avec un seul mouvement (Adili et al. 2021). Pour cette collaboration, j'ai été principalement impliqué dans les différentes discussions de recherche ainsi que dans la supervision de l'étudiant de master qui a mené l'étude. Dans une deuxième collaboration, nous avons exploré l'effet que peuvent avoir d'autres paramètres de la marche (degré de balancement du tronc et vitesse de marche) dans un contexte légèrement différent, lié à l'évitement des collisions avec les piétons. Plus précisément, nous avons exploré l'influence

---

de ces deux paramètres sur la stratégie d'évitement de collision des participants lorsqu'ils traversent un piéton en réalité virtuelle (Bourgaize et al. 2021). Pour cette collaboration, je me suis principalement impliqué dans les aspects expérimentaux en concevant et en conduisant l'expérience.

# BIBLIOGRAPHY

---

- Adili, Robin, Benjamin Niay, Katja Zibrek, Anne-Hélène Olivier, Julien Pettré, and Ludovic Hoyet (2021), « Perception of Motion Variations in Large-Scale Virtual Human Crowds », *in: Motion, Interaction and Games*, pp. 1–7.
- Allen, Brett, Brian Curless, and Zoran Popović (2002), « Articulated body deformation from range scan data », *in: ACM Transactions on Graphics (TOG)* 21.3, pp. 612–619.
- Andriacchi, TP, JA Ogle, and JO Galante (1977), « Walking speed as a basis for normal and abnormal gait measurements », *in: Journal of biomechanics* 10.4, pp. 261–268.
- Arikan, Okan and David A Forsyth (2002), « Interactive motion generation from examples », *in: ACM Transactions on Graphics (TOG)* 21.3, pp. 483–490.
- Armstrong, William W and Mark W Green (1985), « The dynamics of articulated rigid bodies for purposes of animation », *in: The visual computer* 1.4, pp. 231–240.
- Al-Asqhar, Rami Ali, Taku Komura, and Myung Geol Choi (2013), « Relationship descriptors for interactive motion adaptation », *in: Proceedings of the 12th ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, pp. 45–53.
- Atkinson, Anthony P, Winand H Dittrich, Andrew J Gemmell, and Andrew W Young (2004), « Emotion perception from dynamic and static body expressions in point-light and full-light displays », *in: Perception* 33.6, pp. 717–746.
- Awai, Lea and Armin Curt (2014), « Intralimb coordination as a sensitive indicator of motor-control impairment after spinal cord injury », *in: Frontiers in human neuroscience* 8, p. 148.
- Aydin, Yahya and Masayuki Nakajima (1999), « Database guided computer animation of human grasping using forward and inverse kinematics », *in: Computers & Graphics* 23.1, pp. 145–154.
- Banton, Tom, Jeanine Stefanucci, Frank Durgin, Adam Fass, and Dennis Proffitt (2005), « The Perception of Walking Speed in a Virtual Environment », *in: Presence: Teleoperators and Virtual Environments* 14.4, pp. 394–406.
- Barclay, Catharine D, James E Cutting, and Lynn T Kozlowski (1978), « Temporal and spatial factors in gait perception that influence gender recognition », *in: Perception & psychophysics* 23.2, pp. 145–152.

- 
- Barliya, Avi, Lars Omlor, Martin A Giese, Alain Berthoz, and Tamar Flash (2013), « Expression of emotion in the kinematics of locomotion », *in: Experimental brain research* 225.2, pp. 159–176.
- Basili, Patrizia, Murat Sağlam, Thibault Kruse, Markus Huber, Alexandra Kirsch, and Stefan Glasauer (2013), « Strategies of locomotor collision avoidance », *in: Gait & posture* 37.3, pp. 385–390.
- Basten, Ben JH van, Sybren A Stüvel, and Arjan Egges (2011), « A hybrid interpolation scheme for footprint-driven walking synthesis. », *in: Graphics Interface*, pp. 9–16.
- Beacco, Alejandro, Nuria Pelechano, Mubbasir Kapadia, and Norman I Badler (2015), « Footstep parameterized motion blending using barycentric coordinates », *in: Computers & Graphics* 47, pp. 105–112.
- Berton, Florian, Ludovic Hoyet, Anne-Hélène Olivier, Julien Bruneau, Olivier Le Meur, and Julien Pettré (2020), « Eye-gaze activity in crowds: impact of virtual reality and density », *in: 2020 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, IEEE, pp. 322–331.
- Bianchi, L, D Angelini, GP Orani, and F Lacquaniti (1998), « Kinematic coordination in human gait: relation to mechanical energy cost », *in: Journal of neurophysiology* 79.4, pp. 2155–2170.
- Bodenheimer, Bobby, Anna V Shleyfman, and Jessica K Hodgins (1999), « The effects of noise on the perception of animated human running », *in: Computer Animation and Simulation'99*, Springer, pp. 53–63.
- Bohannon, Richard W. (1997), « Comfortable and maximum walking speed of adults aged 20—79 years: reference values and determinants », *en, in: Age and Ageing* 26.1, pp. 15–19.
- Bonnefoy-Mazure, A. and Stéphane Armand (Jan. 2015), « Normal gait », English, *in: Orthopedic Management of Children with Cerebral Palsy*, pp. 199–214.
- Borel, Liliane, Françoise Harlay, Christophe Lopez, Jacques Magnan, André Chays, and Michel Lacour (Apr. 2004), « Walking performance of vestibular-defective patients before and after unilateral vestibular neurectomy », *en, in: Behavioural Brain Research* 150.1-2, pp. 191–200.
- Borghese, N Alberto, L Bianchi, and F Lacquaniti (1996), « Kinematic determinants of human locomotion. », *in: The Journal of physiology* 494.3, pp. 863–879.
- Bourgaize, Sheryl, Michael Cinelli, Florian Berton, Benjamin Niay, Ludovic Hoyet, and Anne-Hélène Olivier (2021), « Walking speed and trunk sway: Influence of an ap-

- 
- proaching person's gait pattern on collision avoidance », *in: Journal of Vision* 21.9, pp. 2023–2023.
- Brand, Matthew and Aaron Hertzmann (2000), « Style machines », *in: Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pp. 183–192.
- Bruderlin, Armin and Tom Calvert (1996), « Knowledge-driven, interactive animation of human running », *in: Graphics interface*, vol. 96, pp. 213–221.
- Bruderlin, Armin and Lance Williams (1995), « Motion Signal Processing », *in: Proceedings of the 22Nd Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '95, New York, NY, USA: ACM, pp. 97–104.
- Bruening, Dustin A, Andrew R Baird, Kelsey J Weaver, and Austin T Rasmussen (2020), « Whole body kinematic sex differences persist across non-dimensional gait speeds », *in: Plos one* 15.8.
- Buchheit, Martin and Alberto Mendez-Villanueva (2014), « Effects of age, maturity and body dimensions on match running performance in highly trained under-15 soccer players », *in: Journal of sports sciences* 32.13, pp. 1271–1278.
- Burke, Michael and Joan Lasenby (2016), « Estimating missing marker positions using low dimensional Kalman smoothing », *in: Journal of biomechanics* 49.9, pp. 1854–1858.
- Buss, Samuel R (2004), « Introduction to inverse kinematics with jacobian transpose, pseudoinverse and damped least squares methods », *in: IEEE Journal of Robotics and Automation* 17.1-19, p. 16.
- Cabrero Daniel, B., R. Marques, L. Hoyet, J. Pettré, and J. Blat (2021), « A Perceptually-Validated Metric for Crowd Trajectory Quality Evaluation », *in: Proceedings of the ACM SIGGRAPH/Eurographics Symposium on Computer Animation*.
- Camarri, Bernadine, Peter R Eastwood, Nola M Cecins, Philip J Thompson, and Sue Jenkins (2006), « Six minute walk distance in healthy subjects aged 55–75 years », *in: Respiratory medicine* 100.4, pp. 658–665.
- Chaminade, Thierry, Jessica Hodgins, and Mitsuo Kawato (May 2007), « Anthropomorphism influences perception of computer-animated characters' actions », *in: Social Cognitive and Affective Neuroscience* 2.3, pp. 206–216.
- Chehab, EF, TP Andriacchi, and J Favre (2017), « Speed, age, sex, and body mass index provide a rigorous basis for comparing the kinematic and kinetic profiles of the lower extremity during walking », *in: Journal of biomechanics* 58, pp. 11–20.

- 
- Chen, Kang, Yupan Wang, Song-Hai Zhang, Sen-Zhe Xu, Weidong Zhang, and Shi-Min Hu (2021), « MoCap-Solver: A neural solver for optical motion capture data », *in: ACM Transactions on Graphics (TOG)* 40.4, pp. 1–11.
- Cho, S.H., J.M. Park, and O.Y. Kwon (Feb. 2004), « Gender differences in three dimensional gait analysis data from 98 healthy Korean adults », *en, in: Clinical Biomechanics* 19.2, pp. 145–152.
- Chouchourelou, Arieta, Toshihiko Matsuka, Kent Harber, and Maggie Shiffrar (2006), « The visual analysis of emotional actions », *in: Social Neuroscience*, 1.1, pp. 63–74.
- Chumanov, Elizabeth S, Cara Wall-Scheffler, and Bryan C Heiderscheit (2008), « Gender differences in walking and running on level and inclined surfaces », *in: Clinical biomechanics* 23.10, pp. 1260–1268.
- Cinelli, Michael E and Aftab E Patla (2007), « Travel path conditions dictate the manner in which individuals avoid collisions », *in: Gait & posture* 26.2, pp. 186–193.
- (2008), « Locomotor avoidance behaviours during a visually guided task involving an approaching object », *in: Gait & posture* 28.4, pp. 596–601.
- Collins, Steve, Andy Ruina, Russ Tedrake, and Martijn Wisse (2005), « Efficient bipedal robots based on passive-dynamic walkers », *in: Science* 307.5712, pp. 1082–1085.
- Coros, Stelian, Philippe Beaudoin, and Michiel Van de Panne (2010), « Generalized biped walking control », *in: ACM Transactions On Graphics (TOG)* 29.4, pp. 1–9.
- Coros, Stelian, Philippe Beaudoin, Kang Kang Yin, and Michiel van de Panne (2008), « Synthesis of constrained walking skills », *in: ACM SIGGRAPH Asia 2008 papers*, pp. 1–9.
- Cutting, James E (1978), « Generation of synthetic male and female walkers through manipulation of a biomechanical invariant », *in: Perception* 7.4, pp. 393–405.
- Cutting, James E, Dennis R Proffitt, and Lynn T Kozlowski (1978), « A biomechanical invariant for gait perception. », *in: Journal of Experimental Psychology: Human Perception and Performance* 4.3, p. 357.
- Cutting, James E. and Lynn T. Kozlowski (1977), « Recognizing friends by their walk: Gait perception without familiarity cues », *in: Bulletin of the psychonomic society* 9.5, pp. 353–356.
- Das, P and G McCollum (1988), « Invariant structure in locomotion », *in: Neuroscience* 25.3, pp. 1023–1034.
- Dayan, E., A. Casile, N. Levit-Binnun, M. A. Giese, T. Hendler, and T. Flash (Dec. 2007), « Neural representations of kinematic laws of motion: Evidence for action-perception

- 
- coupling », en, *in: Proceedings of the National Academy of Sciences* 104.51, pp. 20582–20587.
- De Lasa, Martin, Igor Mordatch, and Aaron Hertzmann (2010), « Feature-based locomotion controllers », *in: ACM Transactions on Graphics (TOG)* 29.4, pp. 1–10.
- Decker, Leslie, Christine Berge, Sabine Renous, and Xavier Penin (2007), « An alternative approach to normalization and evaluation for gait patterns: Procrustes analysis applied to the cyclograms of sprinters and middle-distance runners », *in: Journal of Biomechanics* 40.9, pp. 2078–2087.
- Decker, Leslie, Sabine Renous, Christine Berge, and Xavier Penin (2006), « Analyse Procruste du cyclogramme de la cheville : comparaison de différentes spécialités de sprint », *in: Comptes Rendus Palevol* 5.3, Cent ans après Marey : Aspects de la morphologie fonctionnelle aujourd’hui, pp. 571–581.
- DeVita, Paul, Rebecca E Fellin, Joseph F Seay, Edward Ip, Nicole Stavro, and Stephen P Messier (2016), « The relationships between age and running biomechanics. », *in: Medicine and science in sports and exercise* 48.1, pp. 98–106.
- Durgin, Frank H., Catherine Reed, and Cara Tigue (Jan. 2007), « Step Frequency and Perceived Self-motion », *in: ACM Trans. Appl. Percept.* 4.1.
- Feng, Andrew, Yazhou Huang, Marcelo Kallmann, and Ari Shapiro (2012), « An analysis of motion blending techniques », *in: International Conference on Motion in Games*, Springer, pp. 232–243.
- Fiset, Félix, Anouk Lamontagne, and Bradford J McFadyen (2020), « Limb movements of another pedestrian affect crossing distance but not path planning during virtual over ground circumvention », *in: Neuroscience letters* 736, p. 135278.
- Frimenko, Rebecca, Cassie Whitehead, and Dustin Bruening (2014), « Do men and women walk differently? A review and meta-analysis of sex difference in non-pathological gait kinematics », *in*.
- Fritsch, Frederick N and Judy Butland (1984), « A method for constructing local monotone piecewise cubic interpolants », *in: SIAM journal on scientific and statistical computing* 5.2, pp. 300–304.
- Fukuchi, Reginaldo K and Marcos Duarte (2008), « Comparison of three-dimensional lower extremity running kinematics of young adult and elderly runners », *in: Journal of sports sciences* 26.13, pp. 1447–1454.
- Gage, JR (1990), « An overview of normal walking », *in: Instructional course lectures* 39, pp. 291–303.

- 
- Gaisbauer, Felix, Philipp Fröhlich, Jannes Lehwald, Philipp Agethen, and Enrico Rukzio (2018), « Presenting a Deep Motion Blending Approach for Simulating Natural Reach Motions. », *in: Eurographics (Posters)*, pp. 5–6.
- Gaisbauer, Felix, Jannes Lehwald, Janis Sprenger, and Enrico Rukzio (2019), « Natural posture blending using deep neural networks », *in: Motion, Interaction and Games*, pp. 1–6.
- Gajer, B, A Durey, C Hanon, and C Thépaut-Mathieu (1997), « La poulaine: une représentation complexe de la foulée », *in: Science & Sports 12*, 24s–25s.
- Ganley, Kathleen J and Christopher M Powers (2005), « Gait kinematics and kinetics of 7-year-old children: a comparison to adults using age-specific anthropometric data », *in: Gait & posture 21.2*, pp. 141–145.
- Geijtenbeek, Thomas and Nicolas Pronost (2012), « Interactive character animation using simulated physics: A state-of-the-art review », *in: Computer graphics forum*, vol. 31, 8, Wiley Online Library, pp. 2492–2515.
- Geijtenbeek, Thomas, Michiel Van De Panne, and A Frank Van Der Stappen (2013), « Flexible muscle-based locomotion for bipedal creatures », *in: ACM Transactions on Graphics (TOG) 32.6*, pp. 1–11.
- Gérin-Lajoie, Martin, Carol L Richards, Joyce Fung, and Bradford J McFadyen (2008), « Characteristics of personal space during obstacle circumvention in physical and virtual environments », *in: Gait & posture 27.2*, pp. 239–247.
- Gérin-Lajoie, Martin, Carol L Richards, and Bradford J McFadyen (2005), « The negotiation of stationary and moving obstructions during walking: anticipatory locomotor adaptations and preservation of personal space. », *in: Motor control 9.3*.
- Gérin-Lajoie, Martin, Janet L Ronsky, Barbara Loitz-Ramage, Ion Robu, Carol L Richards, and Bradford J McFadyen (2007), « Navigational strategies during fast walking: A comparison between trained athletes and non-athletes », *in: Gait & posture 26.4*, pp. 539–545.
- Geyer, Hartmut and Hugh Herr (2010), « A muscle-reflex model that encodes principles of legged mechanics produces human walking dynamics and muscle activities », *in: IEEE Transactions on neural systems and rehabilitation engineering 18.3*, pp. 263–273.
- Givon, Uri, Gabriel Zeilig, and Anat Achiron (2009), « Gait analysis in multiple sclerosis: characterization of temporal–spatial parameters using GAITRite functional ambulation system », *in: Gait & posture 29.1*, pp. 138–142.

- 
- Gleicher, Michael (July 1998), « Retargeting Motion to New Characters », *in: Proceedings of ACM SIGGRAPH 98*, Annual Conference Series, ACM SIGGRAPH, pp. 33–42.
- Goldie, Patricia A., Thomas A. Matyas, and Owen M. Evans (1996), « Deficit and change in gait velocity during rehabilitation after stroke », *in: Archives of Physical Medicine and Rehabilitation* 77.10, pp. 1074–1082.
- Goswami, Ambarish (1998), « A new gait parameterization technique by means of cyclogram moments: Application to human slope walking », *in: Gait & posture* 8.1, pp. 15–36.
- Goudriaan, Marije, Ilse Jonkers, Jaap H van Dieen, and Sjoerd M Bruijn (2014), « Arm swing in human walking: what is their drive? », *in: Gait & posture* 40.2, pp. 321–326.
- Gouelle, Arnaud, Julien Leroux, Jonathan Bredin, and Fabrice Mégrot (2016), « Changes in gait variability from first steps to adulthood: normative data for the gait variability index », *in: Journal of motor behavior* 48.3, pp. 249–255.
- Grasso, R, L Bianchi, and F Lacquaniti (1998), « Motor patterns for human gait: backward versus forward locomotion », *in: Journal of neurophysiology* 80.4, pp. 1868–1885.
- Grieve, D.W. (1968), « Gait patterns and the speed of walking », *in: Biomedical Engineering* 3.1, pp. 119–122.
- Grochow, Keith, Steven L. Martin, Aaron Hertzmann, and Zoran Popović (Aug. 2004), « Style-Based Inverse Kinematics », *in: 23.3*, pp. 522–531.
- Gross, M Melissa, Elizabeth A Crane, and Barbara L Fredrickson (2012), « Effort-shape and kinematic assessment of bodily expression of emotion during gait », *in: Human movement science* 31.1, pp. 202–221.
- Halovic, Shaun and Christian Kroos (2018), « Walking my way? Walker gender and display format confounds the perception of specific emotions », *in: Human Movement Science* 57, pp. 461–477.
- Hejrati, Babak, Sam Chesebrough, K Bo Foreman, Jake J Abbott, and Andrew S Merriweather (2016), « Comprehensive quantitative investigation of arm swing during walking at various speed and surface slope conditions », *in: Human movement science* 49, pp. 104–115.
- Ho, Edmond SL, Taku Komura, and Chiew-Lan Tai (2010), « Spatial relationship preserving character motion adaptation », *in: ACM SIGGRAPH 2010 papers*, pp. 1–8.
- Hof, At L. (1996), « Scaling gait data to body size », English, *in: Gait & Posture* 4.3, pp. 222–223.

- 
- Holden, Daniel (2018), « Robust solving of optical motion capture data by denoising », *in: ACM Transactions on Graphics (TOG)* 37.4, pp. 1–12.
- Holden, Daniel, Taku Komura, and Jun Saito (2017), « Phase-functioned neural networks for character control », *in: ACM Transactions on Graphics (TOG)* 36.4, pp. 1–13.
- Holden, Daniel, Jun Saito, and Taku Komura (2016), « A deep learning framework for character motion synthesis and editing », *in: ACM Transactions on Graphics (TOG)* 35.4, pp. 1–11.
- Hollman, John H., Eric M. McDade, and Ronald C. Petersen (2011), « Normative spatiotemporal gait parameters in older adults », *in: Gait & Posture* 34.1, pp. 111–118.
- Hoyet, Ludovic, Anne-Hélène Olivier, Richard Kulpa, and Julien Pettré (July 2016), « Perceptual Effect of Shoulder Motions on Crowd Animations », *in: ACM Transactions on Graphics* 35.4, 53:1–53:10.
- Hoyet, Ludovic, Kenneth Ryall, Katja Zibrek, Hwangpil Park, Jehee Lee, Jessica Hodgins, and O’Sullivan Carol (Nov. 2013), « Evaluating the Distinctiveness and Attractiveness of Human Motions on Realistic Virtual Bodies », *in: ACM Transactions on Graphics* 32.6, 204:1–204:11.
- Huang, Yazhou and Marcelo Kallmann (2010), « Motion parameterization with inverse blending », *in: International Conference on Motion in Games*, Springer, pp. 242–253.
- Iachini, Tina, Yann Coello, Francesca Frassinetti, Vincenzo Paolo Senese, Francesco Galante, and Gennaro Ruggiero (2016), « Peripersonal and interpersonal space in virtual and real environments: Effects of gender and age », *in: Journal of Environmental Psychology* 45, pp. 154–164.
- Ikemoto, Leslie, Okan Arikan, and David Forsyth (2006), « Knowing when to put your foot down », *in: Proceedings of the 2006 symposium on Interactive 3D graphics and games*, pp. 49–53.
- Johansson, Gunnar (1973), « Visual perception of biological motion and model for its analysis », *in: Perception & Psychophysics* 14.2, pp. 201–211.
- Jokisch, Daniel, Irene Daum, and Nikolaus F Troje (2006), « Self Recognition versus Recognition of others by Biological Motion: Viewpoint-Dependent Effects », *in: Perception* 35.7, pp. 911–920.
- Jokisch, Daniel and Nikolaus F. Troje (May 2003), « Biological motion as a cue for the perception of size », *in: Journal of Vision* 3.4, pp. 252–264.

- 
- JudgeRoy, James Oat, III Davis B., and Sylvia Öunpuu (Nov. 1996), « Step Length Reductions in Advanced Age: The Role of Ankle and Hip Kinetics », *in: The Journals of Gerontology: Series A* 51A.6, pp. M303–M312.
- Kallmann, Marcelo (2008), « Analytical inverse kinematics with body posture control », *in: Computer animation and virtual worlds* 19.2, pp. 79–91.
- Kern, Robert S, David L Penn, Junghee Lee, William P Horan, Steven P Reise, Kevin N Ochsner, Stephen R Marder, and Michael F Green (2013), « Adapting social neuroscience measures for schizophrenia clinical trials, Part 2: trolling the depths of psychometric properties », *in: Schizophrenia bulletin* 39.6, pp. 1201–1210.
- Kerrigan, D Casey, Mary K Todd, and Ugo Della Croce (1998), « Gender differences in joint biomechanics during walking: normative study in young adults. », *in: American journal of physical medicine & rehabilitation* 77.1, pp. 2–7.
- Kerrigan, D.Casey, Laura W. Lee, James J. Collins, Patrick O. Riley, and Lewis A. Lipsitz (2001), « Reduced hip extension during walking: Healthy elderly and fallers versus young adults », *in: Archives of Physical Medicine and Rehabilitation* 82.1, pp. 26–30.
- Knechtle, Beat, Christoph Alexander Rüst, Thomas Rosemann, and Romuald Lepers (2012), « Age-related changes in 100-km ultra-marathon running performance », *in: Age* 34.4, pp. 1033–1045.
- Kovar, Lucas, Michael Gleicher, and Frédéric Pighin (July 2002a), « Motion Graphs », *in: ACM Trans. Graph.* 21.3, pp. 473–482.
- Kovar, Lucas, John Schreiner, and Michael Gleicher (2002b), « Footskate Cleanup for Motion Capture Editing », *in: Proceedings of the 2002 ACM SIGGRAPH/Eurographics Symposium on Computer Animation, SCA '02, San Antonio, Texas: ACM*, pp. 97–104.
- Kozlowski, Lynn T. and James E. Cutting (1977), « Recognizing the sex of a walker from a dynamic point-light display », *in: Perception & Psychophysics* 21.6, pp. 575–580.
- Kulpa, Richard, Franck Multon, and Bruno Arnaldi (2005), « Morphology-independent representation of motions for interactive human-like animation », *in: Computer Graphics Forum* 24.3, pp. 343–351.
- Kulpa, Richard, Anne-Hélène Olivier, Jan Ondřej, and Julien Pettré (2011), « Imperceptible relaxation of collision avoidance constraints in virtual crowds », *in: Proceedings of the 2011 SIGGRAPH Asia Conference*, pp. 1–10.
- Lai, Peggy P.K., Aaron K.L. Leung, Agnes N.M. Li, and M. Zhang (Jan. 2008), « Three-dimensional gait analysis of obese adults », *in: Clinical Biomechanics* 23, S2–S6.

- 
- Lau, Manfred, Ziv Bar-Joseph, and James Kuffner (2009), « Modeling spatial and temporal variation in motion data », *in: ACM Transactions on Graphics (TOG)* 28.5, pp. 1–10.
- Laufer, Yocheved (May 2005), « Effect of Age on Characteristics of Forward and Backward Gait at Preferred and Accelerated Walking Speed », *in: The Journals of Gerontology: Series A* 60.5, pp. 627–632.
- Laumond, Jean-Paul, Mehdi Benallegue, Justin Carpentier, and Alain Berthoz (2017), « The yoyo-man », *in: The International Journal of Robotics Research* 36.13-14, pp. 1508–1520.
- Lee, David N (1980), « Visuo-motor coordination in space-time », *in: Advances in psychology*, vol. 1, Elsevier, pp. 281–295.
- Lee, Jehee, Jinxiang Chai, Paul S. A. Reitsma, Jessica K. Hodgins, and Nancy S. Pollard (July 2002), « Interactive Control of Avatars Animated with Human Motion Data », *in: ACM Trans. Graph.* 21.3, pp. 491–500.
- Lee, Se Won, Joe Verghese, Roe Holtzer, Jeannette R Mahoney, and Mooyeon Oh-Park (2014), « Trunk sway during walking among older adults: norms and correlation with gait velocity », *in: Gait & posture* 40.4, pp. 676–681.
- Lee, Seunghwan, Moonseok Park, Kyoungmin Lee, and Jehee Lee (2019), « Scalable muscle-actuated human simulation and control », *in: ACM Transactions On Graphics (TOG)* 38.4, pp. 1–13.
- Li, Jiefeng, Chao Xu, Zhicun Chen, Siyuan Bian, Lixin Yang, and Cewu Lu (2021), « Hybrik: A hybrid analytical-neural inverse kinematics solution for 3d human pose and shape estimation », *in: Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition*, pp. 3383–3393.
- Lim, Yoong Ping, Yi-Chung Lin, and Marcus G Pandy (2013), « Muscle function during gait is invariant to age when walking speed is controlled », *in: Gait & posture* 38.2, pp. 253–259.
- Loula, Fani, Sapna Prasad, Kent Harber, and Maggie Shiffrar (2005), « Recognizing people from their movement. », *in: Journal of Experimental Psychology: Human Perception and Performance* 31.1, p. 210.
- Ma, Wanli, Shihong Xia, Jessica K Hodgins, Xiao Yang, Chunpeng Li, and Zhaoqi Wang (2010), « Modeling style and variation in human motion », *in: Proceedings of the 2010 ACM SIGGRAPH/Eurographics Symposium on Computer Animation, SCA '10*, pp. 21–30.

- 
- Marey, Etienne-Jules (1894), *Le mouvement*, G. Masson.
- Mather, George and Linda Murdoch (1994), « Gender discrimination in biological motion displays based on dynamic cues », *in: Proceedings of the Royal Society of London. Series B: Biological Sciences* 258.1353, pp. 273–279.
- McDonnell, Rachel, Sophie Jörg, Jessica K. Hodgins, Fiona Newell, and Carol O’Sullivan (Feb. 2009a), « Evaluating the Effect of Motion and Body Shape on the Perceived Sex of Virtual Characters », *in: ACM Trans. Appl. Percept.* 5.4, 20:1–20:14.
- McDonnell, Rachel, Sophie Jörg, Joanna McHugh, Fiona N. Newell, and Carol O’Sullivan (Sept. 2009b), « Investigating the Role of Body Shape on the Perception of Emotion », *in: ACM Trans. Appl. Percept.* 6.3, 14:1–14:11.
- McDonnell, Rachel, Michéal Larkin, Simon Dobbyn, Steven Collins, and Carol O’Sullivan (Aug. 2008), « Clone Attack! Perception of Crowd Variety », *in: ACM Trans. Graph.* 27.3, pp. 1–8.
- McDonnell, Rachel, Michéal Larkin, Benjamín Hernández, Isaac Rudomin, and Carol O’Sullivan (2009c), « Eye-catching crowds: saliency based selective variation », *in: ACM Transactions on Graphics (TOG)* 28.3, pp. 1–10.
- Menz, Hylton B., Stephen R. Lord, and Richard C. Fitzpatrick (Aug. 2003), « Acceleration patterns of the head and pelvis when walking on level and irregular surfaces », *in: Gait & Posture* 18.1, pp. 35–46.
- Meyns, Pieter, Sjoerd M Bruijn, and Jacques Duysens (2013), « The how and why of arm swing during human walking », *in: Gait & Posture* 38.4, pp. 555–562.
- Min, Jianyuan and Jinxiang Chai (2012), « Motion graphs++ a compact generative model for semantic motion analysis and synthesis », *in: ACM Transactions on Graphics (TOG)* 31.6, pp. 1–12.
- Minderhoud, Michiel M and Piet HL Bovy (2001), « Extended time-to-collision measures for road traffic safety assessment », *in: Accident Analysis & Prevention* 33.1, pp. 89–97.
- Moissenet, Florent, Fabien Leboeuf, and Stéphane Armand (2019), « Lower limb sagittal gait kinematics can be predicted based on walking speed, gender, age and BMI », *in: Scientific reports* 9.1, pp. 1–12.
- Montepare, Joann M and Leslie Zebrowitz-McArthur (1988), « Impressions of people created by age-related qualities of their gaits. », *in: Journal of personality and social psychology* 55.4, p. 547.

- 
- Murakami, Rumi and Yohei Otaka (2017), « Estimated lower speed boundary at which the walk ratio constancy is broken in healthy adults », *in: Journal of Physical Therapy Science* 29.4, pp. 722–725.
- Murray, M.P., R.C. Kory, B.H. Clarkson, and S.B. Sepic (1966), « Comparison of free and fast speed walking patterns of normal men », *in: American Journal of Physical Medicine* 45.1, pp. 8–24.
- Nagasaki, Hiroshi, Hajime Itoh, Ken Hashizume, Taketo Furuna, Hitoshi Maruyama, and Takashi Kinugasa (1996), « Walking patterns and finger rythm of older adults », *in: Perceptual and Motor Skills* 82, pp. 435–447.
- Natta, Françoise and Chantal Réga (2000), « Analyse cinétique et cinématique:-du départ de sprint en starting-blocks-de la foulée de course à vitesse maximale », PhD thesis, Institut National du Sport et de l'Education Physique (INSEP).
- Niay, Benjamin, Anne-Hélène Olivier, Katja Zibrek, Julien Pettré, and Ludovic Hoyet (2020), « Walk ratio: Perception of an invariant parameter of human walk on virtual characters », *in: ACM Symposium on Applied Perception 2020*, pp. 1–9.
- Olivier, Anne-Hélène, Antoine Marin, Armel Crétual, Alain Berthoz, and Julien Pettré (2013), « Collision avoidance between two walkers: Role-dependent strategies », *in: Gait & posture* 38.4, pp. 751–756.
- Osoba, Muyinat Y, Ashwini K Rao, Sunil K Agrawal, and Anil K Lalwani (2019), « Balance and gait in the elderly: A contemporary review », *in: Laryngoscope Investigative Otolaryngology* 4.1, pp. 143–153.
- Paker, Nurdan, Derya Bugdayci, Goksen Goksenoglu, Demet Tekdöş Demircioğlu, Nur Kesiktaş, and Nurhan Ince (2015), « Gait speed and related factors in Parkinson's disease », *in: Journal of physical therapy science* 27.12, pp. 3675–3679.
- Park, Sang Il, Hyun Joon Shin, and Sung Yong Shin (2002), « On-line locomotion generation based on motion blending », *in: Proceedings of the 2002 ACM SIGGRAPH/Eurographics symposium on Computer animation*, pp. 105–111.
- Peng, Xue Bin, Pieter Abbeel, Sergey Levine, and Michiel van de Panne (2018), « Deepmimic: Example-guided deep reinforcement learning of physics-based character skills », *in: ACM Transactions on Graphics (TOG)* 37.4, pp. 1–14.
- Pinzone, Ornella, Michael H. Schwartz, and Richard Baker (Feb. 2016), « Comprehensive non-dimensional normalization of gait data », *in: Gait & Posture* 44, pp. 68–73.

- 
- Polyakov, Felix, Eran Stark, Rotem Drori, Moshe Abeles, and Tamar Flash (2009), « Parabolic movement primitives and cortical states: merging optimality with geometric invariance », in: *Biological Cybernetics* 100.2, pp. 159–184.
- Pražák, Martin, Ludovic Hoyet, and Carol O’Sullivan (2011), « Perceptual Evaluation of Footskate Cleanup », in: *Proceedings of the 2011 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, SCA ’11, Vancouver, British Columbia, Canada: Association for Computing Machinery, pp. 287–294.
- Pražák, Martin, Rachel McDonnell, and Carol O’Sullivan (2010), « Perceptual evaluation of human animation timewarping », in: *ACM SIGGRAPH ASIA 2010 Sketches*, pp. 1–2.
- Pražák, Martin and Carol O’Sullivan (2011), « Perceiving human motion variety », in: *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization*, pp. 87–92.
- Pronost, N, G Nicolas, G Dumont, and F Multon (2005), « Combining morphological interpolation and biomechanical inverse kinematics to simulate bipedal locomotion », en, in: *Visualization, Imaging, And Image Processing: Fifth IASTED International Conference Proceedings*, p. 7.
- Pronost, Nicolas, Georges Dumont, and Gilles Berillon (2003), « Interpolation Morphologique et Posturale pour la Simulation de Mouvement d’un Humanoïde Virtuel », in: *16emes Journees de l’AFIG*, pp. 121–128.
- Rajagopal, Apoorva, Christopher L Dembia, Matthew S DeMers, Denny D Delp, Jennifer L Hicks, and Scott L Delp (2016), « Full-body musculoskeletal model for muscle-driven simulation of human gait », in: *IEEE transactions on biomedical engineering* 63.10, pp. 2068–2079.
- Ralston, Henry J (1958), « Energy-speed relation and optimal speed during level walking », in: *Internationale Zeitschrift für Angewandte Physiologie Einschliesslich Arbeitsphysiologie* 17.4, pp. 277–283.
- Rapos, Victoria, Michael Cinelli, Natalie Snyder, Armel Crétual, and Anne-Hélène Olivier (2019), « Minimum predicted distance: Applying a common metric to collision avoidance strategies between children and adult walkers », in: *Gait & posture* 72, pp. 16–21.
- Rapos, Victoria, Michael E Cinelli, Robyn Grunberg, Sheryl Bourgaize, Armel Cretual, and Anne-Hélène Olivier (2021), « Collision avoidance behaviours between older adult and young adult walkers », in: *Gait & Posture* 88, pp. 210–215.

- 
- Reitsma, Paul S. A. and Nancy S. Pollard (2003), « Perceptual Metrics for Character Animation: Sensitivity to Errors in Ballistic Motion », in: *ACM SIGGRAPH 2003 Papers*, SIGGRAPH '03, San Diego, California: Association for Computing Machinery, pp. 537–542.
- Ren, JingLi, ZhuBin Zheng, and ZhongMing Jiao (2010), « Simulation of virtual human running based on inverse kinematics », in: *2010 2nd International Conference on Education Technology and Computer*, vol. 3, IEEE, pp. V3–360.
- Romkes, Jacqueline and Katrin Bracht-Schweizer (2017), « The effects of walking speed on upper body kinematics during gait in healthy subjects », in: *Gait & posture* 54, pp. 304–310.
- Rose, Charles, Michael F Cohen, and Bobby Bodenheimer (1998), « Verbs and adverbs: Multidimensional motion interpolation », in: *IEEE Computer Graphics and Applications* 18.5, pp. 32–40.
- Rowe, Erynne, Marla K. Beauchamp, and Janie Astephen Wilson (2021), « Age and sex differences in normative gait patterns », in: *Gait & Posture* 88, pp. 109–115.
- Safonova, Alla and Jessica K. Hodgins (2005), « Analyzing the Physical Correctness of Interpolated Human Motion », in: *Proceedings of the 2005 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, SCA '05, Los Angeles, California: Association for Computing Machinery, pp. 171–180.
- Schreiber, Céline and Florent Moissenet (July 2019), « A multimodal dataset of human gait at different walking speeds established on injury-free adult participants », in: *Scientific Data* 6.1, p. 111.
- Segers, Veerle, Peter Aerts, M Lenoir, and Dirk De Clercq (2006), « Spatiotemporal characteristics of the walk-to-run and run-to-walk transition when gradually changing speed », in: *Gait & posture* 24.2, pp. 247–254.
- Segers, Veerle, Kristof De Smet, Ine Van Caekenberghe, Peter Aerts, and Dirk De Clercq (2013), « Biomechanics of spontaneous overground walk-to-run transition », in: *Journal of Experimental Biology* 216.16, pp. 3047–3054.
- Sekiya, Noboru and Hiroshi Nagasaki (May 1998), « Reproducibility of the walking patterns of normal young adults: test-retest reliability of the walk ratio(step-length/step-rate) », en, in: *Gait & Posture* 7.3, pp. 225–227.
- Sekiya, Noboru, Hiroshi Nagasaki, Hajime Ito, and Taketo Furuna (1997), « Optimal Walking in Terms of Variability in Step Length », in: *Journal of Orthopaedic & Sports Physical Therapy* 26.5, pp. 266–272.

- 
- Sekiya, Noboru, Hiroshi Nagasaki, Hajime Itoh, and Taketo Furuna (1996), « The invariant relationship between step length and step rate during free walking », *in: Journal of Human Movement Studies* 30, pp. 241–257.
- Senden, R, K Meijer, IC Heyligers, HHCM Savelberg, and B Grimm (2012), « Importance of correcting for individual differences in the clinical diagnosis of gait disorders », *in: Physiotherapy* 98.4, pp. 320–324.
- Silva-Hamu, Tânia, Cibelle Kayenne Martins Roberto Formiga, Flávia Martins Gervásio, Darlan Martins Ribeiro, Gustavo Christofolletti, and Jônatas de França Barros (June 2013), « The impact of obesity in the kinematic parameters of gait in young women », *en, in: IJGM*, p. 507.
- Sinclair, Jonathan, Andrew Greenhalgh, Christopher James Edmundson, Daryl Brooks, and Sara Jane Hobbs (2012), « Gender differences in the kinetics and kinematics of distance running: implications for footwear design », *in: International Journal of Sports Science and Engineering* 6.2, pp. 118–128.
- Taylor, Graham W and Geoffrey E Hinton (2009), « Factored conditional restricted Boltzmann machines for modeling motion style », *in: Proceedings of the 26th annual international conference on machine learning*, pp. 1025–1032.
- Taylor, Graham W, Geoffrey E Hinton, and Sam T Roweis (2011), « Two Distributed-State Models For Generating High-Dimensional Time Series. », *in: Journal of Machine Learning Research* 12.3.
- Terrier, Philippe and Yves Schutz (Nov. 2003), « Variability of gait patterns during unconstrained walking assessed by satellite positioning (GPS) », *in: European Journal of Applied Physiology* 90.5, pp. 554–561.
- Troje, Nikolaus. F. (2002), « Decomposing biological motion: A framework for analysis and synthesis of human gait patterns », *in: Journal of Vision* 2, pp. 371–387.
- Vallis, Lori Ann and Bradford J McFadyen (2003), « Locomotor adjustments for circumvention of an obstacle in the travel path », *in: Experimental brain research* 152.3, pp. 409–414.
- Viviani, Paolo and Carlo Terzuolo (1982), « Trajectory determines movement dynamics », *in: Neuroscience* 7.2, pp. 431–437.
- Wang, Jack M, Samuel R Hamner, Scott L Delp, and Vladlen Koltun (2012), « Optimizing locomotion controllers using biologically-based actuators and objectives », *in: ACM Transactions on Graphics (TOG)* 31.4, pp. 1–11.

- 
- Wang, Jing and Bobby Bodenheimer (2003), « An evaluation of a cost metric for selecting transitions between motion segments. », *in: Symposium on Computer Animation*, vol. 2, 3, Citeseer.
- (2004), « Computing the duration of motion transitions: an empirical approach », *in: Proceedings of the 2004 ACM SIGGRAPH/Eurographics symposium on Computer animation*, pp. 335–344.
- (Mar. 2008a), « Synthesis and Evaluation of Linear Motion Transitions », *in: ACM Trans. Graph.* 27.1.
- (2008b), « Synthesis and evaluation of linear motion transitions », *in: ACM Transactions on Graphics (TOG)* 27.1, pp. 1–15.
- Whittle, Michael W (1991), *Gait analysis: an introduction*, Butterworth-Heinemann.
- Winter, David A, Aftab E Patla, James S Frank, and Sharon E Walt (1990), « Biomechanical walking pattern changes in the fit and healthy elderly », *in: Physical therapy* 70.6, pp. 340–347.
- Witkin, Andrew and Zoran Popovic (1995), « Motion Warping », *in: Proceedings of the 22nd Annual Conference on Computer Graphics and Interactive Techniques*, SIGGRAPH '95, pp. 105–108.
- Wobbrock, Jacob O, Leah Findlater, Darren Gergle, and James J Higgins (2011), « The aligned rank transform for nonparametric factorial analyses using only anova procedures », *in: Proceedings of the SIGCHI conference on human factors in computing systems*, pp. 143–146.
- Woollacott, Marjorie H and Pei-Fang Tang (1997), « Balance control during walking in the older adult: research and its implications », *in: Physical therapy* 77.6, pp. 646–660.
- Yin, KangKang, Stelian Coros, Philippe Beaudoin, and Michiel Van de Panne (2008), « Continuation methods for adapting simulated skills », *in: ACM SIGGRAPH 2008 papers*, pp. 1–7.
- Yin, KangKang, Kevin Loken, and Michiel Van de Panne (2007), « Simbicon: Simple biped locomotion control », *in: ACM Transactions on Graphics (TOG)* 26.3, 105–es.
- Zago, Myrka, Adam Matic, Tamar Flash, Alex Gomez-Marin, and Francesco Lacquaniti (2018), « The speed-curvature power law of movements: a reappraisal », *in: Experimental brain research* 236.1, pp. 69–82.
- Zarrugh, M. Y., F. N. Todd, and H. J. Ralston (1974), « Optimization of energy expenditure during level walking », *in: Europ. J. Appl. Physiol.* 33.4, pp. 293–306.

- 
- Zhou, Yi, Zimo Li, Shuangjiu Xiao, Chong He, Zeng Huang, and Hao Li (2018), « Auto-Conditioned Recurrent Networks for Extended Complex Human Motion Synthesis », *in: International Conference on Learning Representations*.
- Zibrek, Katja, Ludovic Hoyet, Kerstin Ruhland, and Rachel McDonnell (July 2015), « Exploring the Effect of Motion Type and Emotions on the Perception of Gender in Virtual Humans », *in: ACM Trans. Appl. Percept.* 12.3, 11:1–11:20.
- Zibrek, Katja, Benjamin Niay, Anne-Hélène Olivier, Ludovic Hoyet, Julien Pettre, and Rachel McDonnell (Nov. 2020), « The Effect of Gender and Attractiveness of Motion on Proximity in Virtual Reality », *in: ACM Trans. Appl. Percept.* 17.4.

---

**Titre :** Évaluation et utilisation des paramètres biomécaniques pour les animations de marche d'humains virtuels

**Mot clés :** Analyse de mouvement, Synthèse de mouvement, Perception, Animation

**Résumé :** Lors de la conception de foules pour des applications de divertissement, quelques mouvements de marche génériques sont dupliqués pour économiser des ressources précieuses, ce qui entraîne un manque de variations. Dans cette thèse, nous étudions l'utilisation potentielle des paramètres biomécaniques de la marche humaine pour générer et modifier des animations de marche spécifiques à diverses caractéristiques d'acteurs (par exemple, l'âge, le sexe, la taille). Nous avons d'abord réalisé une étude utilisateurs pour évaluer la capacité des observateurs à reconnaître un ratio de marche spécifique lorsqu'il est appliqué à des personnages virtuels et nous avons constaté que les principales caractéristiques du ratio de

marche étaient perçues par les observateurs. Nous avons ensuite étendu cette étude en étudiant plus de paradigmes afin de mieux cibler les caractéristiques qui contribuent le plus à la perception du ratio de marche. Enfin, nous avons proposé un cadre pour générer des animations de marche du bas du corps basées sur la poulaine (trajectoire de la cheville vue dans le référentiel de la hanche) et évalué son utilisation à travers une étude perceptive. En conclusion, nous avons montré que les spectateurs sont sensibles aux paramètres biomécaniques de la marche humaine pour l'animation de personnages et nous fournissons des lignes directrices pour concevoir des animations respectant ces paramètres.

---

**Title:** Evaluation and use of biomechanical parameters for virtual humans walking animations

**Keywords:** Motion analysis, Motion synthesis, Perception, Animation

**Abstract:** When designing crowds for entertaining applications, a few generic walking motions are duplicated to save valuable resources, leading to a lack of variations. In this thesis, we investigate the potential use of biomechanical parameters of human walking to generate and edit walking animations that are specific to various actor's characteristics (e.g. age, gender, height). We first performed a user study to evaluate the ability of observers to recognize a specific Walk Ratio (WR) when applied on virtual characters and found that the main characteristics of the WR were perceived by observers.

We then extended this study by investigating more paradigm to better target which features contribute more to the perception of the WR. Finally, we proposed a framework to generate lower body walking animations based on the poulaine (ankle trajectory as seen in the hip reference frame), and evaluated its use through a user study. In conclusion, we showed that viewers are sensitive to biomechanical parameters of human walking for character animation and we provide guidelines to design animations respecting such parameters.