



Design et Évaluation de Systèmes 3D pour la Transmission de Mouvement Dansé

Manon Vialle

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Manon Vialle. Design et Évaluation de Systèmes 3D pour la Transmission de Mouvement Dansé. Vision par ordinateur et reconnaissance de formes [cs.CV]. Université Grenoble Alpes [2020-..], 2023. Français. NNT : 2023GRALM077 . tel-04629920

HAL Id: tel-04629920

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THÈSE

Pour obtenir le grade de

DOCTEUR DE L'UNIVERSITÉ GRENOBLE ALPES

École doctorale : MSTII - Mathématiques, Sciences et technologies de l'information, Informatique

Spécialité : Informatique

Unité de recherche : Laboratoire Jean Kuntzmann

Design et Évaluation de Systèmes 3D pour la Transmission de Mouvement Dansé

Design and Evaluation of 3D Systems for Movement Transmission in Dance

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MSTII
Mathématiques, Sciences et Technologies de l'Information, Informatique

THÈSE

pour obtenir le titre de

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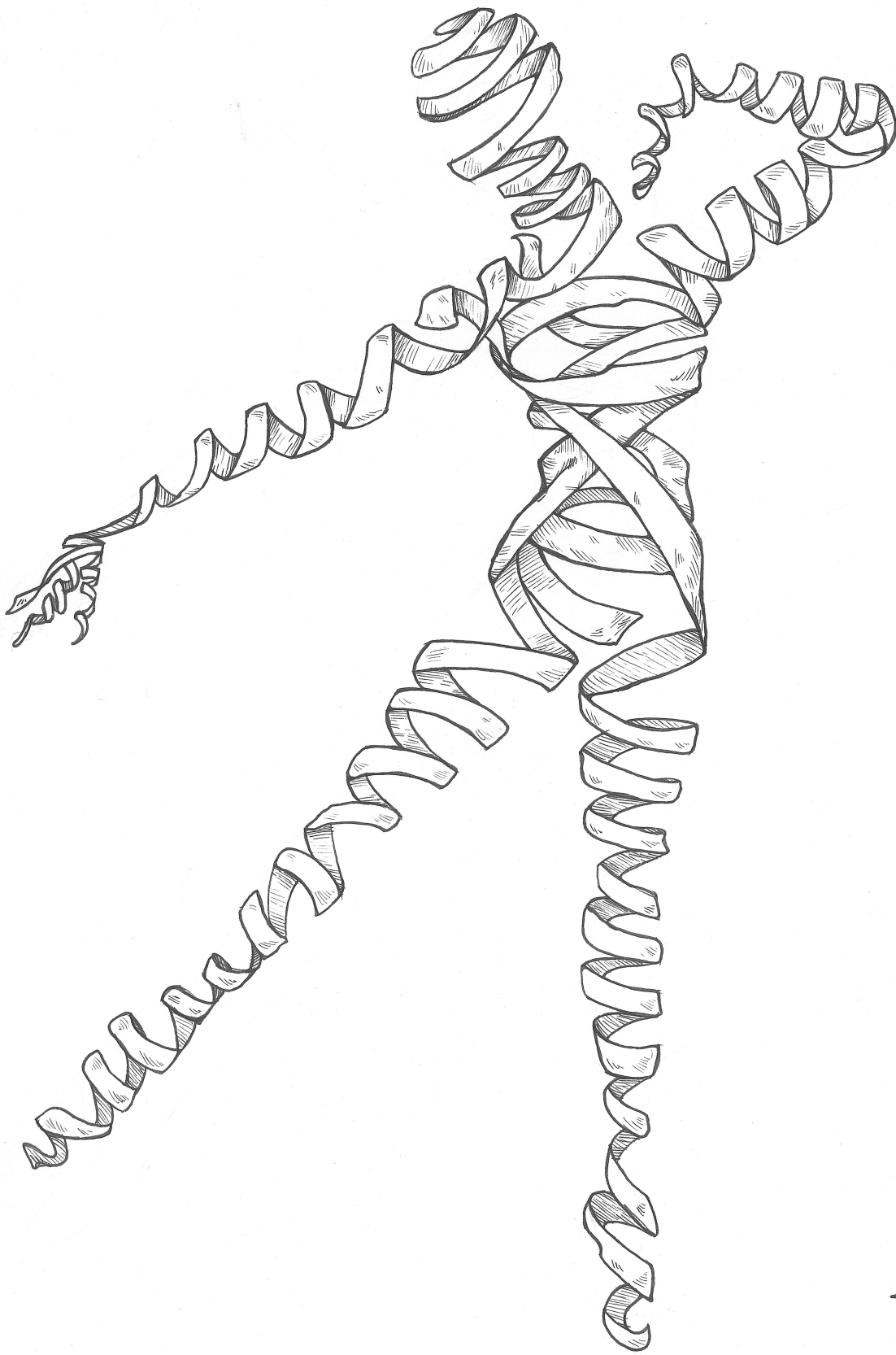
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**Design and Evaluation of 3D Systems for Movement
Transmission in Dance**

Thèse dirigée par Emmanuelle Crépeau
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soutenue le 11 décembre 2023

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Zeco 24/2020

Remerciements

On dit qu'il faut tout un village pour élever un enfant, et je pense que cette expression est tout aussi valable pour un doctorant. Voilà donc, je l'espère, ma manière de remercier mon village, sans lequel je n'aurais pas réussi la moitié de cette thèse.

Je tiens tout d'abord à remercier mes deux rapporteurs, Antonio Camurri et Michael Neff, d'avoir pris le temps de relire mon manuscrit et pour vos retours pertinents et les discussions constructives qui ont suivi. Je souhaite aussi remercier mes rapportrices, Katerina El Raheb, Caroline Larboulette et Laurence Nigay, d'avoir accepté de faire partie de mon jury et pour votre enthousiasme vis-à-vis de ma recherche.

Je tiens à remercier mon expert CSI, Nicolas Pronost, pour les nombreux échanges scientifiques qui m'ont grandement aidé à améliorer ma recherche.

Je tiens ensuite à remercier mes encadrantes. À Emmanuelle, merci de m'avoir prise sous ton aile et accepté de diriger ma thèse, ainsi que pour tout ce que tu as fait pour que ma thèse se déroule dans les meilleures conditions. Merci à Sarah pour avoir créé un projet si intéressant et m'avoir permis d'en faire partie. Merci de m'avoir introduit au merveilleux monde de l'IHM et d'avoir partagé le même enthousiasme que moi dans la recherche en danse. Enfin, je souhaite remercier Mélina Skouras de m'avoir fait confiance et de m'avoir donné une grande liberté dans ma recherche. Tu as su me guider à chaque étape de mon parcours de doctorante, et je t'en suis extrêmement reconnaissante. Merci d'avoir cru en moi depuis mon stage d'introduction à la recherche il y a 5 ans et d'avoir continué à me soutenir à travers les étapes de ma carrière de doctorante.

Je souhaite grandement remercier Élisabeth de m'avoir transmis tes connaissances et ta passion pour la danse de Duncan. Ton enthousiasme pour nos projets et ton énergie à toute épreuve ont été moteurs pour la réalisation de nos projets. Je peux dire que j'ai grandi en tant que danseuse grâce à tes enseignements. Je te remercie aussi d'avoir été intéressée par nos discussions scientifiques, même si les équations restent si mystérieuses. Créer un projet art-science est une tâche compliquée, et ce fut un plaisir de le faire à tes côtés.

Au-delà de l'encadrement scientifique, je n'aurais pas pu mener cette thèse à bout sans le soutien de mes amis et de mes collègues. En tout premier lieu, je souhaite remercier mes collègues du LJK. Que ce soit à travers un bonjour à la pause café ou à travers de longs débats pendant un délicieux repas du CROUS, toutes ces interactions créent une ambiance bienveillante et chaleureuse qui m'a fait très vite me sentir chez moi, dans une période où j'en avais vraiment besoin. Je pense sincèrement que l'ambiance de notre laboratoire est précieuse et qu'elle participe à la bonne réussite des doctorants dans cette tâche au



combien difficile. J'espère que cette ambiance perdurera longtemps. Une mention spéciale aux non-permanents, avec qui j'ai partagé tant de pause café, de gâteaux d'anniversaires, de soirées d'Halloween, de séances de volley, de BBQ et tant d'autres événements : Margaux, JB, Carlos, Flora, Selim, Thibaut, Simon, Waiss, Victor, Yanis, Hippolyte, Dima, Benji, Claudia, Qiao, Hubert, Yunjiao, Anatole, Angelique, et toutes les personnes que j'ai pu oublier. À mes co-bureaux passés et présents : Gilles, Nils, Eloi, Julien, Hélène, Alexandre, merci d'avoir à la fois maintenu une ambiance studieuse mais aussi su détendre l'atmosphère en périodes de rush (et désolée de vous avoir imposé mes chansons de Taylor Swift). Et merci aux permanents qui ont toujours su être de bons conseils : Brigitte, Sergei, Boris, Sylvain, Manel, Kévin, Grégory, Eric et tant d'autres. À Laurence Wazné, merci pour tout ce que tu as fait pour le bon déroulement de ma thèse, je t'en serais éternellement reconnaissante.

Je souhaiterais aussi remercier deux collègues en particulier. Tout d'abord, Emmanuel Rodriguez, mon co-thésard, avec qui j'ai partagé des moments de stages jusqu'à la fin de nos thèses. On a commencé ensemble et on s'est soutenu jusqu'au bout, malgré l'isolement du covid, et finalement, on y est arrivé tous les deux ! Ensuite, je voudrais remercier un collègue malgré lui : mon collocataire Ernest. On n'avait pas prévu en se mettant en collocation que l'on passerait notre première année de thèse en tant que collègues, dans notre appartement grenoblois. Merci pour toutes les gaufres et les glaces partagées, les moments où nos deux neurones restants jouent au ping-pong, les soirées salsa, les fous-rires sur IsAbElLe, les jumpscars et j'en passe. Merci aussi pour ton soutien lors de mes périodes de doute. Tu as toujours été plus confiant que moi dans ma recherche, et je t'en suis grandement reconnaissante. À nous deux, pour avoir fini nos doctorats. J'espère que tu me réserveras toujours une salsa ou une bachata (ou une kizENT). Mais tu resteras toujours le papy de notre binôme ;))

À Mathilde et Murielle, merci de m'avoir soutenue à travers ces nombreuses années, même si mon travail vous paraît parfois très abstrait. J'espère que nous aurons encore de nombreux churos à partager, et bien sûr toujours à moins de 10 minutes à pied ;))

Merci à Chloé, d'être toujours là pour des discussions philosophiques sur nos vies respectives, peu importe nos périodes de vies. Et merci de toujours croire en moi.

Je tiens tout particulièrement à remercier Isabelle et Tristan Debeaupuis de m'avoir accueillie pendant mon mois et demi à Antony. Votre générosité m'a beaucoup touchée, et sans cela, je n'aurais pas pu mener mon projet à bout. Ce fut un plaisir d'être votre colocataire temporaire.

Je souhaite aussi remercier l'équipe ANIMA pour leur accueil et pour m'avoir introduit au monde de la recherche au début de ma thèse.

Je tiens aussi à remercier l'équipe ExSitu pour m'avoir accueillie et formée pendant un

mois et demi. Ce fut un plaisir de découvrir le monde de l'IHM à vos côtés. Je tiens à remercier tout particulièrement les non-permanents de l'équipe qui m'ont intégrée dans leur groupe et m'ont fait me sentir chez moi à Saclay. Merci à Romane, Alex Kabil, Alex Battut, Arthur, Camille, Martin et une spéciale dédicace à la team Navigo+.

Merci à la team UC, Gaétan, Olivier et Antoine, pour avoir été ma deuxième maison à Grenoble. Je me rappellerai les séances de muscu pour que j'aie des gros bibis, les séances de télétravail dans votre salon en plein covid, les nombreuses nuits passées sur votre canapé (pas si confortable que ça) à cause du couvre-feu.

Merci à tous mes amis et ma famille parisiens de m'avoir accueillie chez vous au cours de mes nombreuses missions. J'espère que le fromage sera toujours une bonne manière de payer le loyer.

À mes filleuls de l'ENSIMAG, Alex et Séréna, qui sont eux aussi dans leurs parcours de thèse, merci de m'avoir encouragée à travers les années. Je n'ai aucun doute sur vos capacités à réussir brillamment dans vos carrières respectives.

À mes amis du Salistan, Thed, Lucille, Brian, Enguerran, Lucie, Romain, Guillaume, Ben, Vivien, Raoul et Titus, merci de m'avoir soutenue dans les moments difficiles, que ce soit à travers un appel, un message ou une longue discussion autour d'un verre.

La danse a été une partie centrale de mon travail de thèse, mais a aussi été pour moi un moyen de m'évader. Je tiens à remercier en premier lieu Marie-Hélène Guilpin, ma professeure de danse lorsque j'étais à Albertville. Tu m'as non seulement appris à danser, mais surtout tu m'as appris à aimer la danse, sous toutes ses formes. Tes enseignements et ta bienveillance ont participé à faire de moi la personne que je suis aujourd'hui. Malgré les blessures, j'ai réussi à suivre de nombreux cours de danse et surtout à m'ouvrir à de nouveaux styles. Je tiens à remercier mes professeurs : Elsa, Johan, Lilly, Anna, Yves et Coralie. Et merci à toutes les personnes avec qui j'ai eu le plaisir de danser.

Je voudrais remercier ma famille d'avoir toujours cru en moi. Une mention toute particulière à ma maman, qui a été la première docteure de ma vie, d'avoir été un modèle pour moi. Tu m'as toujours laissé énormément d'indépendance et tu m'as aidée à devenir la femme que je suis aujourd'hui.

Enfin, je souhaite dédier cette thèse à mes grands-parents Alice et Pierre, pour qui la réussite académique a été une manière de s'émanciper. J'espère que d'où vous êtes, vous êtes fiers de moi.



Conception et Évaluation de Systèmes 3D pour la Transmission de Mouvement Dansé

Résumé — Dans cette thèse, mon objectif est de concevoir et d'évaluer des systèmes 3D pour la transmission du mouvement en danse. J'explore la transmission de la danse à travers deux dimensions : la transmission de certains aspects spécifiques d'un style de danse aux danseurs, et la transmission d'une animation de danse d'un personnage virtuel animé à un autre. Lors de la transmission d'aspects spécifiques d'un style de danse aux danseurs, j'ai collaboré avec une danseuse experte dans le style d'Isadora Duncan pour créer des systèmes 3D en réalité augmentée. Une première contribution réside dans la co-conception, la mise en œuvre technique et l'évaluation avec les danseurs d'un artefact virtuel qui transmet la fluidité du mouvement. Ce système permet de visualiser des rubans en forme d'étoile joints au plexus solaire, animés à partir de données de capture de mouvement des danses d'Isadora Duncan. L'animation est créée via un algorithme d'optimisation. L'évaluation s'est déroulée sous la forme d'ateliers et a montré un grand potentiel du système pour transmettre les qualités du mouvement d'Isadora Duncan qu'une représentation de type humain ou basée sur un squelette échoue à transmettre. Sur la base des retours de la première contribution, j'ai co-conçu avec la même danseuse experte un second système qui vise à aider la perception de la spatialisation de la danse en réalité augmentée. Cette deuxième contribution réside dans la conception et l'évaluation du système. Avec la danseuse experte, nous nous sommes inspirées de la notation Sutton pour créer un système qui visualise des poses clés animées à partir de la danse et la trace du plexus solaire dans l'espace. J'ai ensuite mené une observation structurée pour évaluer les différences dans le nombre d'images clés affichées en même temps. Mes résultats montrent le potentiel de la réalité augmentée à des fins pédagogiques. La dernière contribution de cette thèse réside dans le deuxième aspect de la transmission de la danse : la transmission de la danse animée d'un personnage virtuel à un autre. J'ai créé un système qui prend en entrée des données de capture de mouvement d'une danse et les transfère à un autre corps qui peut avoir une morphologie différente. Pour ce faire, je génère d'abord des rubans à partir des données de capture de mouvement (squelette animé ou ensemble de marqueurs). Ensuite, j'associe chaque ruban à une chaîne articulée du squelette cible. Enfin, j'applique l'animation contenue dans les rubans sur le squelette cible à l'aide d'un algorithme d'optimisation.

Mots clés : réalité augmentée, animation par ordinateur, danse, visualisation de mouvement, rubans, IHM

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Design and Evaluation of 3D Systems for Movement Transmission in Dance

Abstract — In this thesis, I aim to design and evaluate 3D systems for movement transmission in dance. I explore dance transmission through two dimensions: transmission of specific aspects of a dance style to dancers and transmission of the animated dance from one virtual animated character to another. When transmitting specific aspects of a dance style to dancers, I collaborated with a connoisseur dancer in Isadora Duncan’s style to create 3D systems in augmented reality. A first contribution is the co-design, technical implementation, and evaluation with dancers of an artifact that transmits the fluidity of movement. This system visualizes star-shaped ribbons joined at the solar plexus animated from motion-captured data of Isadora Duncan’s dances. The animation is performed using an optimization-based algorithm. The evaluation took place as a series of workshops. It showed great potential for the system to transmit the qualities of Isadora Duncan’s movement that a human-like or skeleton-based representation fails to transmit. Based on the feedback of the first contribution, I co-designed with the same connoisseur dancer another system that supports the perception of spatiality in dance in augmented reality. This second contribution lies in the design and evaluation of the system. Along with the expert dancer, I took inspiration from the Sutton notation to create a system that visualizes animated keyframes of the dance and the trace of the solar plexus in space. I then ran a structured observation to evaluate the differences in the number of keyframes displayed simultaneously. My results show the potential of augmented reality for pedagogical purposes. The last contribution of this thesis lies in the second aspect of dance transmission: transmission of the animated dance from one virtual animated character to another. I created a system that takes as an input motion-captured data of a dance and transfers it to another body with a different morphology. To achieve this, I first generate ribbons from the motion-captured data (animated rig or set of markers). Then, I match each ribbon with an articulated chain of the target rig. Lastly, I apply the animation contained in the ribbons onto the target rig using an optimization algorithm.

Keywords: augmented reality, computer animation, dance, movement visualisation, ribbons, HCI

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Acronyms and abbreviations

AR	Augmented Reality
VR	Virtual Reality
XR	Mixed Reality
HCI	Human Computer Interaction
Mocap	Motion Capture
ICH	Intangible Cultural Heritage
DILS	Dance Interactive Learning Systems
LMA	Laban Motion Analysis



CHAPTER 1

Introduction

1.1 Context

During the 2003 Convention for Safeguarding of the Intangible Cultural Heritage organized by UNESCO, Intangible Cultural Heritage (ICH) was defined as “*the practices, representations, expressions, knowledge, skills - as well as the instruments, objects, artifacts, and cultural spaces associated therewith - that communities, groups and, in some cases, individuals recognize as part of their cultural heritage*”(UNESCO 2003). Dance practices, as they are a part of performing arts, are a significant part of ICH. Similarly to other practices in ICH, dance has historically relied on the transmission of its traditions through oral and kinesthetic transmission. Because of the fragile way in which Intangible Cultural Heritages are transmitted, (UNESCO 2003) advocates in favor of academic research whose goal is to support the safeguarding of ICH. The rise of new technologies, such as videotaping and, more recently, motion capture, has provided new opportunities for preserving and transmitting dance practices because they enable a lasting capture of the performed movement. These new technologies bring together the fields of dance, human-computer interaction, and computer graphics to open new opportunities for safeguarding the invaluable knowledge embedded in dance traditions, spanning diverse cultures and styles such as Greek and Cyprus Folks dances (Aristidou et al. 2021), Indian classical dance (Mallik et al. 2011), Chinese Kasidawen dance (Papangelis et al. 2016). A dance style that aligns closely with the principles of Intangible Cultural Heritage (ICH) preservation is Isadora Duncan’s.

1.2 The Isadora Duncan Living Archive

Isadora Duncan (1877-1927) is considered as one of the founders of modern and contemporary dance. In her choreographic work, Duncan wanted to move away from the rigid technique imposed by ballet to recover what she described as “the natural movement”. In her definition, natural movement is described as unrestricted, respecting both the structure of the body and the pull of gravity: “*Such movements will always have to depend on and correspond to the form that is moving*” (Duncan 1928). That is, each movement that a



dancer performs is seen through the lens of said dancer's body. In this same philosophy to find "natural movement", she also expressed that the center of movement and energy is the solar plexus. Thus, all movement in her choreography comes from the solar plexus, which is an anatomical point located on the torso between the diaphragm and the sternum.

Isadora Duncan always refused to be filmed because she thought that the frame rate of the camera at the time (about 24 frames per second) was not enough to represent the fluidity of her choreography. Thus, choreography has primarily been transmitted orally and kinesthetically from one generation to another. Although part of her repertoire has been translated into dance notation (such as Laban notation and Sutton notation) as a way to try to archive and safeguard her choreographic knowledge, those notations are hard to decipher and not well known amongst the dance community. Moreover, they do not transcribe the philosophy of movement of the choreographer. Nowadays, only very few dancers are experts in the repertoire of Isadora Duncan, and it is no longer transmitted in the regular dance curriculum. One can even go as far as considering it in danger of extinction.

The Isadora Living Archive project has been created to address the concerns of safeguarding Isadora Duncan's repertoire and ensure its preservation. This project is a collaboration between my supervisors Sarah Fdili Alaoui (Inria Paris Saclay team Ex-Situ), Rémi Ronfard and Mélina Skouras (Inria Grenoble team ANIMA), the MocapLab, the French National Dance Center (Centre National de la Danse), the expert dancer in Isadora Duncan's style, Elisabeth Schwartz, and myself (Laboratoire Jean Kuntzmann Grenoble). As a first step of this project, we recorded with the MocapLab a set of Isadora Duncan's dance pieces performed by Elisabeth using motion capture technology. Then, using this motion-captured data, we aimed to create tools that help to safeguard Isadora Duncan's dance and transmit its motion qualities to a large public.

1.3 Research Questions

Within the Isadora Duncan Living Archive project and through my Ph.D., I focused on the topic of *dance transmission*. Indeed, as described in the previous section, Duncan's philosophy of teaching and transmitting her dance lies in the dancer understanding her philosophy of movement to make the movement their own and to feel the qualities of her dance in their body, as opposed to mimic what they see and reproducing it. In essence, the goal is not to *mimic* but to *embody*.

A way of safeguarding her work while still following her philosophy is, therefore, to focus on transmitting her dance qualities and not on simply creating a collection of video recordings of her students performing her dance pieces. That is why, in this thesis, I focused on

designing systems that transmit dance qualities.

More specifically, I first focused on the transmission of specific qualities of Duncan's dance style: the solar plexus, the wave, and fluidity. I asked the following research question:

How can Isadora Duncan's movement's qualities be represented?

To address this question, I followed, along with my supervisors, a three-year-long co-design with a connoisseur process with our collaborator and expert in the style of Isadora Duncan, Elisabeth Schwartz. As a dancer who trained in ballet for more than 20 years and who more recently opened her training to new dance styles such as contemporary, urban dance, and salsa, I used my dance knowledge to communicate with Elisabeth and to create designs that I would like to be using in the dance studio. On the other hand, as a computer scientist, I used my computer graphics and human-computer interaction skills to implement and evaluate the designed artifacts.

Through the first phase of this co-design process, we created an abstract visualization of a dancing body made of 5 flexible ribbons joined together at the solar plexus. We included this 3D model in an augmented reality headset in order for users to see the model dancing in space. We then evaluated the model with dancers. From the feedback of the dancers emerged the second research question:

How can the perception of space be enhanced in dance using augmented reality?

To address this question, I continued in the co-design process with Elisabeth. We were inspired by a dance notation called Sutton to create a system that visualizes our ribbon models, animated "keyframes" and the trajectory that the solar plexus leaves in space.

Lastly, we drew inspiration from the ribbon model and the *line of action* depicted in Guay et al. 2013 to create a third system. The line of action is a 2D line drawn by cartoonists to help them pose characters. In their work, Guay et al. 2013 created a system that poses a 3D skeleton (used for animating characters) from a drawn line of action, mimicking the cartoonist's work. We compared our generated ribbon to the line of action and thought the ribbons could pose another skeleton using a similar process. If this operation is performed on the set of ribbons of one dance of Isadora Duncan, this would animate the resulting character. The last research question is:

How can the ribbon model be used to transfer a dance animation from one animated character to another?

To address this question, we created an optimization based system that animates a skeleton from our animated ribbon using a spring energy. We were able to transfer the animation to humanoids skeletons with various number of bones and bone length.



1.4 Contributions

The contributions of this thesis are listed below:

1.4.1 Design Contributions

During the co-design process, the following contributions were made:

- The design of a new 3D abstract representation of a dancing body. This model is made of five flexible ribbons joined together at the solar plexus to represent a dancing body and is animated from motion-captured data.
- The design of a system that visualizes the animated ribbons, along with animated keyframes that we called moments of impulse and the trajectory of the solar plexus, to improve the visualization of space in the Hololens 2 headset.
- The deep understanding of Isadora Duncan’s philosophy of movement through our three-year-long co-design process with an expert dancer in the style of Isadora Duncan

1.4.2 Experimental Contributions

Throughout our evaluation with dancers, we made the following contributions:

- The evaluation with dancers during two workshops of our star-shaped ribbon model. Findings show that this abstract representation faithfully conveys Isadora Duncan’s movement’s qualities.
- The structured observation of our system that supports the perception of space with dancers. Our findings suggest that there is not one system that fits all needs, but rather a variety of systems for various uses, from observing to dancing, to improvising with the system.

1.4.3 Computer Animation Contributions

The contributions of this thesis in computer animation are listed below:

- A new way of animating ribbons from motion captured data using the discrete elastic rod's framework introduced in (Bergou et al. 2008). The parameters of this framework are then studied using visual and numerical results.
- A novel way to transfer dance motion animation from one animated character using the ribbons as lines of action. The ribbons are generated from the input dance animation. Then, the target skeleton is animated using an optimization algorithm at each time step.

1.5 Structure of the Manuscript

This manuscript is structured around three parts, each addressing one of the three research questions defined in the previous section. This structure is detailed as follows:

- **Chapter 2** describes previous work in the context of dance transmission through visualization of a dancing body, augmented ways to learn movement, sketch-based animation of dance motion, and motion retargeting.
- **Part One: How Can Isadora Duncan's Movement's Qualities be Represented?**
 - **Chapter 3** describes the collaboration with the dancer Elisabeth Schwartz through a co-design process and the first iterative design process of an abstract visualization of Isadora Duncan's dance. The final design is a set of five flexible ribbons joined together at the solar plexus.
 - **Chapter 4** describes the method to animate the designed ribbons from motion-captured data and the choice of parameters of the mathematical model.
 - **Chapter 5** describes the evaluation of the ribbon model with professional dancers through two workshops using a 2D screen and an augmented reality headset.
- **Part Two: How Can the Perception of Space be Enhanced in Dance using Augmented Reality?**
 - **Chapter 6** builds on the results from chapter 5 to improve the model displayed in augmented reality to support the perception of space. The new system was created while observing a co-design process with our expert dancer, Elisabeth Schwartz.
 - **Chapter 7** describes the structured observation (Garcia et al. 2014) of three variations of this aforementioned system during a workshop with dancers.



- **Part Three: How Can the Ribbon Model be Used to Transfer a Dance Animation from one Animated Character to Another?**
 - **Chapter 8** describes a novel way to use the ribbons generated in chapter 4 to transmit dance motion from one animated skeleton to another. This chapter describes on-going work.
- **Chapter 9** discusses the thesis results and possible opportunities to broaden in future work.

1.6 Publications

The contributions from chapters 3, 4 and 5 led to the following peer-reviewed publication in the Creativity and Cognition conference:

Manon Vialle, Sarah Fdili Alaoui, Mélina Skouras, Vennila Vilvanathan, Elisabeth Schwartz, and Remi Ronfard (2022). “Visualizing Isadora Duncan’s Movements Qualities”. In: *Creativity and Cognition*. C&C ’22. Venice, Italy: Association for Computing Machinery, pp. 196–207

The contribution from chapters 6 and 7 led to the following peer-reviewed publication in the Creativity and Cognition conference:

Manon Vialle, Sarah Fdili Alaoui, Mélina Skouras, and Elisabeth Schwartz (2023). “Supporting Perception of Spatiality in Dance in Augmented Reality”. In: *Proceedings of the 15th Conference on Creativity and Cognition*. C&C ’23. Virtual Event, USA: Association for Computing Machinery, pp. 441–453

CHAPTER 2

State of the Art

Mixing computer science with dance has been the focus of researchers for a long time. One of the first attempts came from Michael Noll (Noll 1967) in *dance magazine* in 1967 and Merce Cunningham (Cunningham 1968) around the same time. In those early discussions, they both suggested representing dance through animated stick figures, which could be used for choreography planning. Ten years later, Savage et al. in (Savage et al. 1978) introduced a computer model named CHOREO, which helped visualize choreography and teach dance notations. Since then, many new topics involving computer science and dance have emerged. In the case of this thesis, we will look at specific fields related to our research topic: archiving dance, dance notation and augmented dance notation, movement representation, augmented ways to learn movement and transmission of dance qualities.

2.1 Archiving Dance

Archiving dance has been a topic of interest in the dance world. Indeed, as dance is an intangible art form, archiving creates a lasting trace of the choreography. Historically, archiving dance in a lasting way has started with dance notations. These first notations were crucial to recovering the choreographic knowledge. For example, in the early 16th century, Raoul Feuillet created the Feuillet notation to archive and transmit baroque dances. This notation still enables us to retrieve those dances today. Since then, many more dance notations have been introduced, such as the Laban notation (Laban 1950) and the Benesh notation (Benesh 1975). Many dance pieces were safeguarded by being written into those notations as a way for dance companies to keep track of their choreography.

Later, with the rise of video cameras, videotaping became the most mainstream way to archive dance. Unlike dance notations that require training to read and write symbolic movement representation, video is more accessible. Nowadays, a humongous amount of choreographic work is archived using videotaping. For instance, the *Numeridanse* website (*Numeridanse*) archives more than 4770 recorded dance videos.

More elaborate systems have been created to archive and safeguard traditional dance practices. In traditional folk dance, Aristidou et al. worked on safeguarding Greek and Cyprus



folk dances by creating a virtual dance museum (Aristidou et al. 2021) from motion-captured data (Aristidou et al. 2014). Mallik et al. created an ontology-based architectural framework allowing users to navigate a cultural heritage repository containing previously annotated videos, images, writing pieces, music, and sculptures. They applied their system to Indian classical dance. In (Papangelis et al. 2016), they advocate for a three-step process for the design of mobile applications to safeguard dance knowledge based on their study of traditional Chinese Kasidawen dance. The three phases are described as documentation of dance traditions, translation of knowledge into new technologies, and co-designing with the dance practitioners to build meaningful systems for the indigenous community.

Researchers and choreographers have also collaborated to design new technological archives focused on the specific style of one choreographer. William Forsyth, along with Volker Kuchelmeister created the CD-ROM *Improvisation Technologies*, a video archive with augmented images to better explain his style (Volker Kuchelmeister 1999).



Figure 2.1 – A screenshot of the living archive website <https://artsexperiments.withgoogle.com/living-archive>

More recently, Wayne McGregor collaborated with Google to create *living archive*, an online interactive archive of McGregor’s previous choreography. In this project, they analyzed 25 years of video recording of McGregor’s choreography and created a visual database of all the poses, classifying them by similarity. The web interface lets the user choose any combination of poses from that database. A new dance sequence is created from the selected poses using a recurrent neural network model (RNN) trained on the set of video recordings of McGregor’s choreography to be able to synthesize new dances (see Figure 2.1).

Within the Isadora Duncan Living archive project, we aim to create an interactive archive of Isadora Duncan’s choreography in collaboration with an expert dancer in this style of dance in an attempt to safeguard her dance knowledge.

2.2 Dance Notations and Augmented Dance Notations

Dance notations are a historical way of archiving dance as described in Section 2.1. Unlike videotaping, notation systems can provide an exhaustive way through language and symbols to keep a written trace of movement and choreographic structures. Indeed, videotaping can obstruct some essential parts of the dance. One of the most well-known notation systems is the Laban Notation introduced by Rudolf Laban (Laban 1950; Laban et al. 1974). The idea of this notation system is to write, through abstract symbols, the positions of each body part in the 3D space, which Laban discretized into what he called a kinesphere (see Figure 2.2a). Another well-known notation system is the Benesh notation introduced by Rudolf Benesh (Benesh 1975) (see Figure 2.2b). The Benesh notation focuses more on the trajectories the body parts leave in space. Another dance notation was introduced later by Valerie Sutton (Sutton 1973) (see Figure 2.2c), where she represents the position of the human body using stick figures on a horizontal stave. One of the main problems with these notations is that they are hard to learn for beginners.

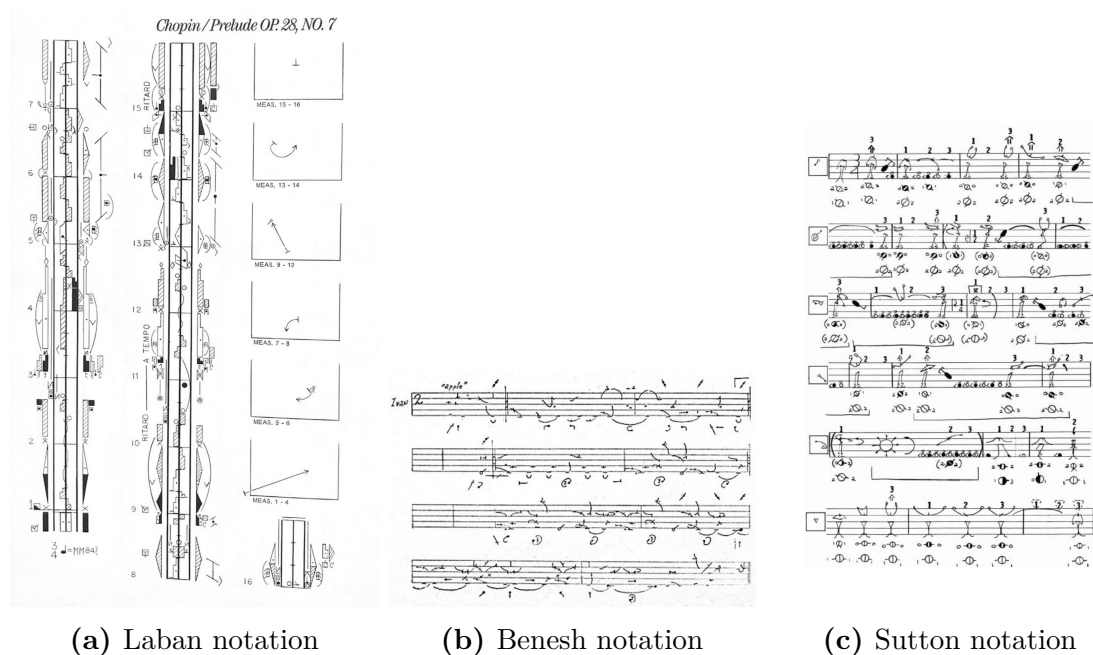


Figure 2.2 – Different dance notations

To make them more accessible, researchers have developed various software systems to visualize the dance that has been notated or notate a dance that has been described.

The first attempt comes from (Savage et al. 1978). In their work, they introduce a com-



puter model named CHOREO, which animates a stick figure from dance motion inputted by the user in the form of the Massine or Laban notation. Later on in (Wilke et al. 2003) and (Wilke et al. 2005), the LabanWriter software enables a user to translate choreography explained in words into a Laban notation and vice-versa. The LabanDancer software interprets the generated files and animates a human mannequin, which follows the choreography. In (Neagle et al. 2004), the team used basic ballet poses to animate a figure dancing a choreography written in the Benesh notation. In (Choensawat et al. 2014), they automatically generate Laban notation from motion-captured data. More recently, the LabanLens project (OSU 2017) provides an application that lets the user create and edit a Laban notation in augmented reality. The augmented reality headset lets users dance while reading the Laban notation. This prevents segmenting the creative process between writing the notation, reading it, and performing it, creating a smooth workflow.

In Chapter 6, we were inspired by the Sutton dance notation, which is particularly suitable for representing the body. We created a 3D system that spatializes the choreography by placing animated stick figures in 3D space. The goal is to help users understand the spatiality of the choreography, as well as its temporality. We motivate the design of a 3D representation of dance movements by the results of the study in (Boer et al. 2018). They compared five different representation of dance movement: Benesh notation, Laban notations, a 2D animation, a 3D animation and auditory description. They found that the 3D animation did not disrupt the dancers, stimulated their creativity, and supported their understanding of the movement better than the 2D animations and the dance notations.

2.3 Representing a Dancing Body

In his dance piece (Préviex 2015), Préviex explores the history of how motion is represented, from chronophotography to data science. One of the historical and intuitive ways of representing a dancing body is using humanoids. The digital dancer is represented as an animated humanoid in the DanceForms software (Calvert et al. 2005).

(Hachimura et al. 2004) studied which representation of the avatar is more suited for dance education in virtual reality (VR). They found that each visualization (skeleton, a humanoid-like character, a humanoid-like character with a visible skeleton, and a more realistic humanoid, see Figure 2.3) suits a different learning modality and enforces the need for a plurality of systems for a plurality of needs. In (Tsampounaris et al. 2016), they studied how augmented human-like avatars can augment learning and understanding of dance movement. They augmented the avatars using particles emitted from the hands and feet and displayed motion trails.

The Choreomorphy project explored different visualizations of a dancer's body (Raheb et

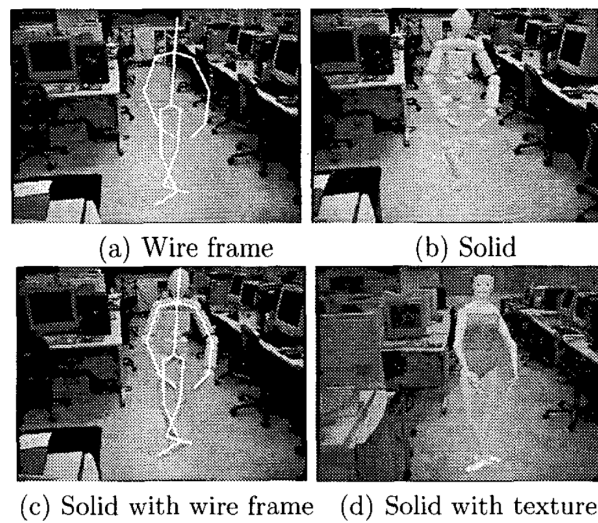


Figure 2.3 – The four representations studied in (Hachimura et al. 2004).

al. 2018). They used a co-design methodology with dancers in order to create a variety of augmented avatars. The resulting avatars were categorized as abstract, anthropomorphic, and cartoonistic with static or animated textures and distorted meshes (see Figure 2.4). Users were led to choose freely the avatar they wanted. They reflected on how each representation influenced how they performed the movement and created different emotions.

Closer to our work, Cisneros et al. describe the Blending Engine (Cisneros et al. 2019a), a creator tool developed as part of the WhoLoDance project (Cisneros et al. 2019b), which lets dance students combine different movements both in time and space. They compare several visualization methods for the dancer’s body, including a stickman, an android, a snowman, and an arrowman (see Figure 2.5). While humanoids seem like the most obvious option to represent dance movements performed by humans, they can sometimes lead to an uncanny effect when trying to make them realistic (Tinwell 2014). In their study reviewing interactive learning systems for dance, (Raheb et al. 2019) highlights that most existing systems in the literature represented the teacher and student with a realistic or skeletal avatar. They argue that playing with different visualization types, especially in less codified dance styles like contemporary dance, can have promising outcomes.

The literature shows many examples of systems representing the body abstractly (beyond humanoids). Both choreographers and researchers have shown much potential in dance. In 1999, in collaboration with choreographer Merce Cunningham, Downie and Kaiser created a model displaying strokes of color representing dance motion in the dance piece *Biped* (Kaiser et al. 2008). In (Fdili Alaoui et al. 2013), Fdili Alaoui et al. studied how different behaviors of mass-spring systems suggest the movement qualities of the choreographer Emio Grecco. Their study shows the suitability of abstract visuals to represent movement



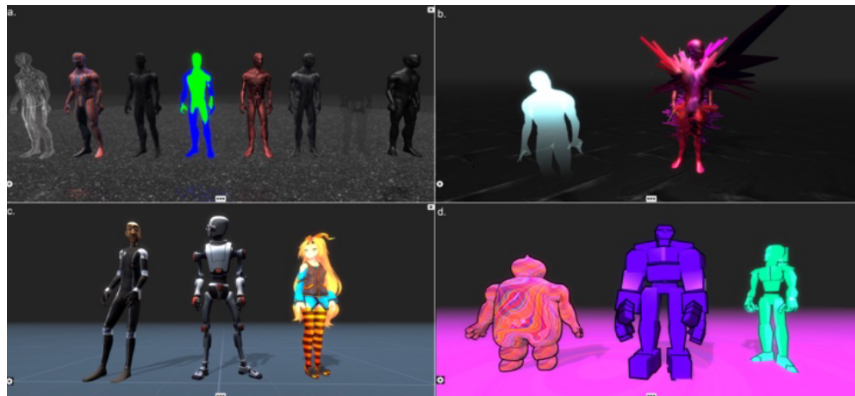


Figure 2.4 – The four representations studied in (Raheb et al. 2018). **Top left:** Abstract Anthropomorphic Static/Animated Textures, **Top right:** Abstract Anthropomorphic Distorted Mesh, **Bottom left:** Cartoonistic Specific, **Bottom right:** Cartoonistic Abstract

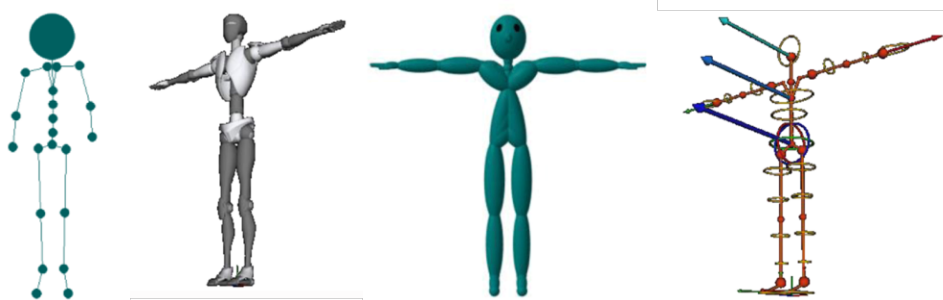


Figure 2.5 – The four representations studied in (Cisneros et al. 2019a). From left to right: a stickman, an android, a snowman, and an arrowman

qualities for dancers. These results echo the study of Leach and Delahunta Leach et al. 2017. In their work, they advocate for a radically abstract representation of the digital body, using arguments from cognitive science and taking examples from their long-lasting collaboration with Marc Downie and Wayne MacGregor. Together, they designed an abstract body for the piece “Becoming”. They created three main requirements for the abstract body: three-dimensional, human scale, and compelling. They achieved this by displaying a dynamic abstract shape on a giant stereoscopic screen. In (Szporer 2014), Denis Poulin and Martine Époque developed a concept of “dance without bodies” using particle animation guided by motion capture data. They show the results in their short film *CODA* showing a virtual performance of Stravinsky’s *Rite of Spring*.

Zhang et al. (Zhang et al. 2018) proposed a system, *MoSculp*, that creates a motion sculpture. The system displays motion by keeping track of the position of essential parts of the body. Then, a 3D surface is created by linking those positions (see Figure 2.6). Their findings show that the motion sculptures give more information about motion than



Figure 2.6 – Resulting Motion sculpture of a dance motion from the MoSculp software (Zhang et al. 2018), taken from their website <http://mosculp.csail.mit.edu/>

existing stroboscopic and space-time visualization methods. (Hsueh et al. 2019) represented movement using multiple abstract visualizations (particles, springs, blobby form, fluid body, and trails). They showed how these visualizations support dancers in creating new movement material (Hsueh et al. 2019). In (Fdili Alaoui et al. 2012), movement qualities based on Emio Greco’s style were translated into an abstract moving light spot to support the user’s exploratory and expressive system use. Valuing a plurality of representation is at the heart of the Digital Body project of choreographer Alexander Whitley (Whitley 2021). The project explores multiple representations of the body based on motion capture data, going from abstract to more literal visualizations.

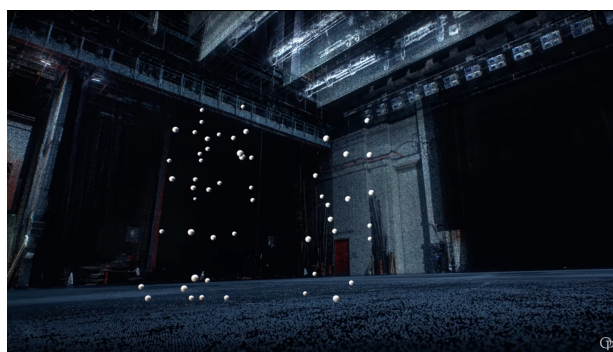


Figure 2.7 – A screenshot of the *CLINAMEN* video project by (Arcier 2020)

In their collaboration with the Paris Opera House in the project *CLINAMEN*, Arcier represent the three dancers performing by just displaying the motion capture markers on their body (Arcier 2020) (see Figure 2.7).

In my work described in Chapter 3, I introduced a model that consists of 5 flexible ribbons joined together at the solar plexus to represent a dancing body. This model has been co-

designed with an expert connoisseur of Isadora Duncan’s repertoire and has been perceived by dancers to convey Duncan’s quality despite – or because of – its abstract representation. Moreover, in our second system defined in Chapter 6, dance spatial motion is also represented as the trace that the solar plexus leaves in space and moments of impulses, which are animated keyframes placed in space along the line.

2.4 Augmented Ways to Learn Movement

Multiple experiments in HCI have provided augmented ways to help students learn dance movements. When referring to augmented ways to learn movement, we refer to systems that use augmented, mixed, or virtual reality to teach movement. The research community has multiple definitions of augmented and mixed reality, as shown in (Speicher et al. 2019). In this thesis, I use the definition that opposes augmented and mixed reality to virtual reality. While a virtual reality set-up immerses the user in a purely virtual environment, augmented and mixed reality set-ups mix both virtual elements with some real-world elements. In my chosen definition, augmented and mixed reality are therefore used interchangeably. Consequently, I will refer to the Hololens 2 headset as an augmented reality headset.

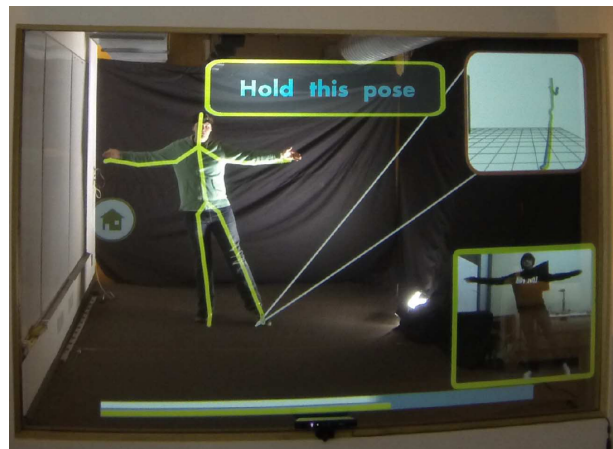


Figure 2.8 – The YouMove system by (Anderson et al. 2013)

Researchers have explored augmenting elements from the dance studio, such as the mirror (Marquardt et al. 2012; Anderson et al. 2013; Molina-Tanco et al. 2017; Trajkova et al. 2018), which play a central role in classical ballet training and are present in most dance studios. (Marquardt et al. 2012) created an AR mirror to guide dancers through learning and to allow them to reflect on their movements and correct them. The mirror overlays the desired dance movement on the student’s reflection as a skeletal stick figure. In Anderson et al. 2013, more information can be added to the augmented mirror, such as a side view of the movement and arrows to display the direction of that movement (see Figure 2.8).

They found that when compared to a video displaying the movement to be performed, the YouMove system improved learning and short-term retention of the dance motion by a factor of 2 compared to a traditional video demonstration. (Trajkova et al. 2018) tested giving audio feedback and compared it to visual with beginner and expert dancers and found that combining both visual and audio feedback would fit those two different publics. Instead of overlaying the direct reflection of that dance with the target motion, (Molina-Tanco et al. 2017) designed the *DelayMirror*, a mirror that displays the movement that the student performs, but with a time delay to let the student reflect on their performance. They tested their system with ballet dancers and found that the *DelayMirror* complements a regular mirror well, as it enables students to look back on a part of their dancing that they could not see with a regular mirror. The use of a mirror is interesting because it fits the classical way of learning dance movement. Usually, dancers dance in front of a mirror to be able to self-correct their movements. However, having movement demonstrated on a 2D screen does not enable the students to move freely in space because they do not see the screen when they move around.

In order to explore the three-dimensionalities of dance, researchers have used VR and AR to have better spatial visualization. In (Sarupuri et al. 2023), they surveyed 292 users of VR platforms for dancing. They found that while dancing in VR is a different experience than dancing in real life, it shows great potential to engage new dancers, such as users with mental and physical health issues, and may open many more avenues of research.

In (Muneesawang et al. 2015), they use the same principals of the augmented mirror of (Anderson et al. 2013) (overlaying the teacher's movement, augmenting it with arrows for direction and giving feedback in the form of a score), but this time immersing the student in a 3D cave. Their findings show that their system helps students slightly improve their performance.

Chan et al. used real-time motion capture to teach dance in VR (Chan et al. 2011) and found that feedback in VR helped students learn movement better than a demonstration with no feedback. More recently, Sra et al. created a VR social system allowing students to participate in dance lessons remotely (Sra et al. 2018). During the dance lesson, two users were put in a shared virtual environment, each having a personal virtual "teacher" (that the other user cannot see). The "teacher" demonstrated simple dance moves (a body wave, a push the roof, a simple 2 steps forward, 2 steps backward, and a side step). They found that VR facilitated such a social way to learn dance remotely. In (Iris et al. 2020), they created a mobile augmented reality platform using Google Cardbord to teach folk dances of *Pašovská Sedlcká*. Their system visualizes an avatar performing the folk dance. They compared two ways of visualizing their system: on a flat screen and using the mobile app with the Google Cardbord¹. They assessed the performance of the beginner

¹https://arvr.google.com/intl/fr_fr/cardboard/



participants by evaluating the difference in poses between the displayed avatar and the user (whose position is tracked using a motion capture set-up). Their results, without significant difference, indicate a tendency for AR applications to help students perform better than with 3D animation presented on a projector screen.



Figure 2.9 – The VR system to teach salsa (Senecal et al. 2020)

While many of these systems focus on learning individual dance styles, there has been research about how to learn couples dance. In (Senecal et al. 2020), a VR platform is created to teach salsa dancing. The student dances with a virtual partner, who responds like a salsa dance partner would based on the leader's dance moves. The position of the feet is also represented on the floor (see Figure 2.9) to teach a small set of basic salsa moves. The student's performance is evaluated using Laban Motion Analysis for motion style and Musical Motion Framework for rhythm accuracy. In their study with beginners and expert dancers, they found a significant difference in scores before and after training with the systems and that beginners after training show scores of regular dancers.

In their study on Dance Interactive Learning Systems (DILS) (Raheb et al. 2019), makes the following suggestions for future designs of DILS:

- following a co-design methodology in order to create DILS that support the practice of dancers
- having portable systems that can be used in the dance studio as opposed to constricted in a lab
- Leveraging on the potential of 3D instead of a 2D screen to render the demonstrated motion
- tailoring the systems to the specific dance style
- going beyond a scoring system as feedback to the student

We took on these recommendations to build our systems. Using a Hololens 2 headset enables one to represent movement in a 3D space. The augmented reality aspect of the headset lets the dancers see the dance studio and the projected 3D visualizations. The Hololens 2 is also highly portable, as it is wireless and does not require any other object than the headset to be used. Augmented reality headsets such as the Hololens have been used in previous exploratory work by (Cisneros et al. 2019a) to visualize their generated dancing avatars, and in (OSU 2017) to visualize and create Laban notation.

Our co-design process with a connoisseur of Isadora Duncan’s work let us dig deep into the dance style and created tailored systems for the Duncanian style to safeguard them. In our work, we provide a more abstract representation of the dance, allowing more freedom in the interpretation and execution of each dance step.

In these previous works, the focus is on learning the steps of a dance piece rather than the particular style in which it should be executed. They focus on feedback in the form of scores, usually describing the difference in the student’s pose compared to the target motion performed by the “teacher”.

2.5 Transmission of Dance Qualities

Rather than just evaluating the accuracy of the poses performed in a dance piece, many researchers have looked into the transmission of dance movement qualities. The primary framework researchers use to analyze movement qualities is the Laban Movement Analysis (LMA) framework (Laban et al. 1974). Introduced by Rudolf Laban, LMA focuses on four aspects of movements: Body, Effort, Space, and Shape.

Body focuses on the body itself, looking at which part of it is moving.

Effort deals with the dynamics and qualities of movement. Movement is categorized into four components: Weight (the amount of energy exerted), Time (the speed and rhythm of movement), Space (the direction and focus of movement), Flow (the smoothness or abruptness of movement)

Shape looks at the configuration of the body and how it changes over time. It involves exploring how movements create and manipulate shapes in space. Within the Shape category, a sub-category, Shape Qualities, can be described with a horizontal change (Spreading or Enclosing), a vertical change (Rising or Sinking), or a sagittal change (Advancing or Retreating).

Space examines how movement occurs in relation to the surrounding environment. It considers spatial concepts like personal space, shared space, and pathways in space.

Researchers in HCI have developed computational systems to characterize dance movement through LMA.

LMA has been used in many research fields (Ziegelmaier et al. 2020) such as computer animation (Bouchard et al. 2007), robotics (Masuda et al. 2009), game design (Zacharatos et al. 2013), movement analysis (Silang Maranan et al. 2014), gesture recognition, interaction design and motion data visualization. One of the earliest works using LMA comes from (Chi et al. 2000). In their work, they developed EMOTE, a system that focuses on the Effort and Shape categories of LMA to animate a 3D character using motion capture data to produce more expressive and natural simulated movements. (Zhao et al. 2005) created a system that extracts LMA characteristics from motion-captured data and video. (Bouchard et al. 2007) built on those two previous works to create a motion segmentation system. They found that this system performs as well as a manual segmentation.

Much of the work done with LMA in HCI regarding dance is made to analyze recorded dance data and translate it into parts of LMA. In (Larboulette et al. 2015), they review the set of computable descriptors of human motion that can be used to describe parts of the LMA system and define motion qualities in general. (Silang Maranan et al. 2014) designed a system, *EffortDetect*, that transforms motion data from a single-accelerometer to Laban Effort qualities using a Machine Learning algorithm. They found that while their system is not more accurate than systems developed in the literature, its accuracy shows great potential for only sensing one part of the body.

LMA has also been used to provide feedback on movement quality to dancers during the learning process. In their system (Aristidou et al. 2015) translate specific motion characteristics into LMA elements of Effort and Space to characterize dance performance. In later work, (Senecal et al. 2020) used the same software based on LMA, along with a rhythm accuracy system, to evaluate the effectiveness of their VR salsa dancing training platform. Similarly, (Jang et al. 2017) introduced a system to evaluate a dancer's motion accuracy using LMA.

While raw motion data can be translated into LMA components using different systems, there has also been work around providing visual and auditory feedback on the LMA extracted features. In Camurri et al. 2016, they built a framework based on four layers: physical signals - virtual sensors, low-level features - time series, mid-level features - trajectories or points in multidimensional (amodal) spaces, and expressive qualities. Their conceptual framework seeks to establish a robust foundation for the development of computational models and systems. They employ this conceptual framework and its implementation to create interactive sonification that converts movement qualities into auditory experiences. Mentis and Johansson built a system using the Microsoft Kinect in which users' Effort qualities were used to trigger musical events (Mentis et al. 2013).

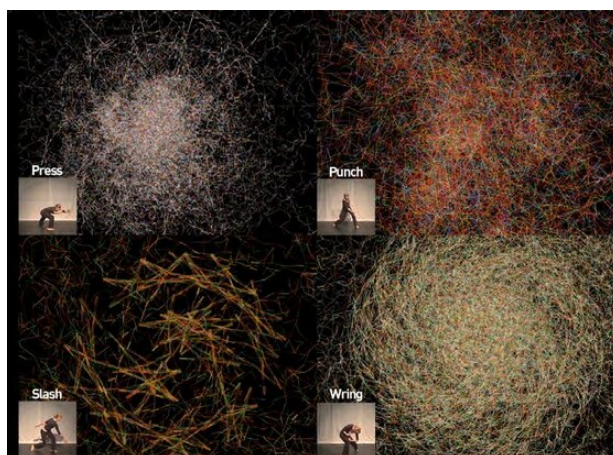


Figure 2.10 – The EMVIZ system of (Subyen et al. 2011)

The EMVIZ system (Subyen et al. 2011) takes LMA information and translates it into a visual effect (see Figure 2.10). This system was used in (Silang Maranan et al. 2014) to create an interactive art installation, during which the audience provided critical feedback regarding their response to the aesthetic and communicative properties of the visualizations. The audience reported that the system helped them increase their awareness and understanding of motion qualities, whether looking at their movement or dancers' movements. In (Fdili Alaoui et al. 2017), they designed a system that translates data from an accelerometer, EMGs, and motion capture system to LMA. They then used this system in three different settings: a dance performance, a participatory design workshop with dancers and choreographers, and a pedagogical workshop for dancers. Throughout these three applications, they showed how this new technology allowed dancers to experience Efforts by providing higher-level movement features and richer computational models while adapting to various artistic and expressive movement practices and contexts. In (Larboulette et al. 2016), they derive LMA components of movement from motion and translate them into visual and dynamical features of a 3D virtual tree (see Figure 2.11). They found that the tree's features are consistent with the effect of emotion on movement. In their study, (Kim et al. 2022) looked at the perceptual consistency and association of the LMA Effort factor. Their findings show that the most consistent element is the Time element, while the least consistent element is the light element. They also found that Effort factors correlate with two or three other Effort factors. This suggests that not all LMA Effort factors are more relevant to visualize than others. Moreover, since some elements can co-occur with other elements, it can be harder to isolate one single element. This suggests that LMA is not always fit to analyze certain movement qualities. Moreover, in the context of dance, (Davis et al. 2021) argues that LMA is not fit for all types of choreographical styles, as it has been designed with a specific western view of motion and dance. They encourage dance students to see it as a tool rather than the only way to describe dance movement.



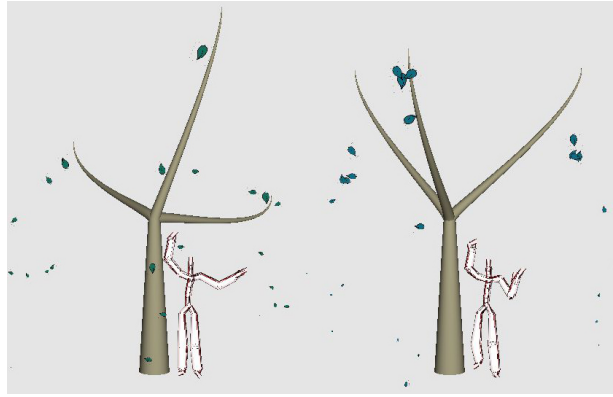


Figure 2.11 – The tree visualization by (Larboulette et al. 2016)

Beyond LMA, researchers have also tried to quantify other dance movement qualities. In (Piana et al. 2016), they introduce a metric to quantify the fluidity of dance movement. However, work has been done without relying on LMA but using movement qualities specific to a particular choreographer's dance style. The work of (Fdili Alaoui et al. 2012) focused on defining motion qualities specific to Emilio Greco's dance style: Breathing, Expanding, and Reducing are extracted by analyzing the oscillatory dynamics and energy of the visitor's hand movements. These properties are mapped on the position and brightness of the light spot. Later, they also created an educational installation entitled Double Skin/Double Mind, which is meant to familiarize dancers with several movement qualities (Fdili Alaoui et al. 2015). The installation attempts to recognize the qualities of Breathing, Jumping, Expanding, and Reducing in the visitor's movement. These sensed qualities are then displayed to the visitor through the behavior of a simulated mass-spring system (see Figure 2.12). (Bisig et al. 2022) collaborated with dancer and choreographer Muriel Romero to create a system that transmits motion qualities specific to her choreographical dance style. They first outlined the qualities: Space - Levitation, Dynamics - Fluidity, Dynamics - Particles, Dynamics - Staccato, Dynamics - Thrusting. Then, they converted those qualities to properties of a long articulated arm made of multiple joints.

In our work described in Chapter 3, we outlined some principal movement qualities of Isadora Duncan: the wave, the solar plexus, and fluidity. Then, considering those design principles, we designed a ribbon model to transmit those qualities. Unlike most of this previous work, we did not try to translate these dance motion qualities into numerical values based on captured movement. Instead, those qualities will be displayed through the ribbon model as an intrinsic characteristic of the ribbon. Moreover, unlike many previous works, we do not aim at giving feedback on performed movement. However, we aim to make those qualities more visible to those looking at the ribbons dancing.



Figure 2.12 – The mass-spring system of (Fdili Alaoui et al. 2015)

2.6 Dance and computer animation

In this section, we will describe previous work relating to the last part of this thesis, which aims at transferring a dance animation from one skeleton to another.

2.6.1 Sketch based animation

Using sketching to keep track of choreography is very common for choreographers. It is even the base of the Sutton notation (see Figure 2.2c). In (Moghaddam et al. 2014), a mix of ballet terms and dance sketching represents the choreography. In (Thorne et al. 2004), a method using three types of sketching lines is used to animate a doodle: sketched links, sketched annotations, and sketch motion. (Carlson et al. 2015) introduced the software *iDanceForm*, which enables a choreographer to sketch choreography using keyframes on a tablet. The resulting choreography is then displayed using an animated avatar. Their study with experts and beginner dancers shows the potential for such systems to support the creative process of creating new choreography.

In (Guay et al. 2013), the authors use the line of action (sketching tool used in the drawing community to draw a first sketch of a future drawing, see Figure 2.13) to describe a pose and then map a mannequin to the line of action. In later work, (Guay et al. 2015b) uses





Figure 2.13 – The line of action drawn by a cartoonist (left), the posed 3D character by (Guay et al. 2013)

the line of action as a way to convey motion in order to animate figures. In (Guay et al. 2015a), a physically-based model is used to simulate the line of action’s motion. First, user-provided strokes are used to forward simulate 2D elastic motion. Then to ensure continuity across keyframes, the forward simulations are retargeted to the drawn strokes. Finally, a 3D character motion is synthesized, matching the dynamic line. The method proposed in Chapter 8 uses sketch-based animation as inspiration to create a retargeting problem. We generate ribbons from the input motion at each time frame, which can be considered as lines of action, and then animate the target skeleton.

2.6.2 Motion retargeting in computer animation

Motion retargeting is the process of transferring a recorded motion from one animated character to another. It has many fields of application, such as robotics to animate a robot or computer animation to use motion-captured data to animate a character. In the context of computer animation, when capturing the motion, the generated skeleton is adapted to the morphology of the person being recorded. If the target skeleton has different proportions, how can this animation be transferred from one skeleton to another?

A first intuition would be to transfer the corresponding angles to the target skeleton. However, this is not always possible as the target skeleton may not have the same number of bones as the input skeleton or the same topology. Moreover, if the target skeleton has different proportions, reporting the rotation angles will lead to poses not being performed well, and if the animation contains contact with other objects or with the ground, there is no guarantee that contact will remain.

When looking at motion retargeting, we aim to transfer the input motion to skeletons that have a shape difference with the input. There exist two main categories of shape differences:

Morphology : two skeletons have different morphologies if they have the same number of bones and bone connections but different bone length, or their rest pose is different.

Topology : two skeletons have the same topology if they have the same equivalent primal skeleton introduced in (Aberman et al. 2020) (that is, the graphs representing their skeletal connections are topologically equivalent). This can be described as the skeletons having the same number of limbs. Usually, all humanoid skeletons have the same topology.

The first attempt to solve such a problem comes from (Gleicher 1998). They introduced a space-time optimization framework with kinematic constraints. Optimization is performed through the entire motion sequence. A year later, (Lee et al. 1999) took a different approach, applying inverse kinematics on the motion to satisfy constraints and then applying a smoothing filter to the motion through multi-level B-spline curve fitting. (Choi et al. 2000) introduced an online retargeting method that computed changes in joint angles corresponding to end-effector position adjustments, preserving high-frequency details of the original motion. (Monzani et al. 2000) introduced a new method using an intermediate skeleton that enables retargeting to skeletons with different morphologies. The intermediate skeleton has the same number of nodes and local axis systems orientation as the target skeleton, but the bones are oriented as the input skeleton nodes. Then, they apply inverse kinematics on the obtained skeleton. (Tak et al. 2005) introduced a physically-based motion retargeting filter, leveraging dynamic constraints for physically plausible motions. Feng et al. 2012 proposed heuristics for mapping arbitrary joints to canonical ones and outlined an algorithm to instill behaviors onto an arbitrary humanoid skeleton.

Classical motion retargeting approaches, like those mentioned above, primarily relied on optimization with hand-crafted kinematic constraints tailored to specific motions, often involving simplifying assumptions. With the increased availability of motion data, data-driven approaches have gained prominence. (Delhaisse et al. 2017) described a method for transferring learned latent representations of motions from one robot to another. (Jang et al. 2018) employed a deep autoencoder to optimize the latent space for desired changes in bone lengths, albeit requiring paired training data.

Several studies have explored retargeting human motion data to non-humanoid characters (Seol et al. 2013; Yamane et al. 2010), where source and target skeletons may significantly differ. However, these approaches require captured motions of a human subject emulating the target character’s style. They also involve selecting key poses from captured motion sequences and matching them to the corresponding character poses or pairing corresponding motions. (Abdul-Massih et al. 2017) proposed representing a character’s motion style through groups of body parts (GBPs) and suggested motion style retargeting across skeleton structures by establishing correspondence between GBPs. This process necessitates defining GBPs and their correspondence for each character pair. In (Aberman et al. 2020),



the skeleton is simplified in the latent space as a primal skeleton, and motion retargeting is performed by decoding the motion in the latent space through the target skeleton.

When looking at retargeting dance motion specifically, researchers focused on retargeting motion from one video to another using machine learning methods (Chan et al. 2019; Ren et al. 2021). However, motion from video lacks information about the depth and displacements in space. In our work, we focus on retargeting the dance movement of Isadora Duncan from one skeleton to another.

In our proposed method in Chapter 8, we use the same metaphor of an intermediate/primal skeleton as (Monzani et al. 2000) and (Aberman et al. 2020). In our approach, the intermediate “skeleton” is the set of animated ribbons described in Chapter 4. The primal and intermediate skeletons have less or equal amounts of joints to the target skeleton. In contrast, our ribbon models have a high number of “joints”, leading to the limbs’ bending to spread more evenly along the articulated chain. In our method, we generate a set of flexible ribbons from the input skeleton, and then, using an optimization-based algorithm, transmit the animation from the ribbons to the target skeleton. We hope that having this intermediate ribbon model captures the essence of the dance movement, and therefore enables to transmit that dance movement onto the target skeleton while keeping its essence.

Part I

How can Isadora Duncan's Movement's Qualities be Represented?



Résumés en français des chapitres

Chapitre 3

Ce chapitre décrit le processus de co-conception d'artefacts 3D avec une experte du style d'Isadora Duncan dans le but de représenter les qualités de mouvement d'Isadora Duncan. Ce processus s'est déroulé en plusieurs étapes : tout d'abord, une explication du style d'Isadora Duncan par notre experte danseuse, à travers des discussions et des démonstrations dansées. Ensuite, nous avons itéré sur un design en incluant notre experte tout au long du processus. Le résultat est un modèle de 5 rubans souples, joints au plexus solaire, animé à partir de données de capture de mouvement.

Chapitre 4

Ce chapitre décrit la manière dont nous avons animé les rubans à partir de données brutes de capture de mouvement. Nous avons utilisé un modèle physique de tige élastique basé sur des énergies pour représenter les rubans. Ensuite, nous avons attaché ces rubans aux positions des marqueurs de capture de mouvement à l'aide de ressorts linéaires et angulaires. Enfin, pour animer ces rubans, nous avons utilisé un algorithme d'optimisation sur l'énergie totale du système, comprenant les énergies de la tige et les énergies des données. Nous décrivons ensuite les choix des différents paramètres du système physique en fonction des besoins liés à la représentation d'un mouvement fluide.

Chapitre 5

Dans ce chapitre, nous décrivons deux études utilisateurs que nous avons menées afin d'évaluer la pertinence de notre modèle pour représenter le mouvement duncanien. Lors du premier atelier, nous avons projeté une vidéo de notre animation sur un écran et avons évalué sa pertinence avec des danseurs. Lors du deuxième atelier, nous avons importé notre modèle dans un casque de réalité augmentée afin de permettre aux danseurs d'observer plus précisément l'aspect en trois dimensions du modèle. Nos résultats montrent que le modèle de ruban à cinq branches permet de bien représenter la philosophie du mouvement d'Isadora Duncan.



CHAPTER 3

Co-designing with a Connoisseur Dancer in Isadora Duncan's Style

3.1 Designing the Elastic Model with the Expert

3.1.1 Co-designing with a Connoisseur

In this Ph.D. thesis, I engaged, along with my supervisors Méline Skouras, Rémi Ronfard and Sarah Fdili Alaoui, in a 3-year long co-design process (Greenbaum et al. 1992) with Elisabeth Schwartz, an expert dancer of Isadora Duncan's dance style. Elisabeth is a third-generation of Isadora Duncan's dancers. She was taught by Julia Levin, who was a student of Anna Duncan, Isadora Duncan's adoptive daughter. Elisabeth has devoted most of her career to learning, studying, teaching, dancing, and sharing Isadora Duncan's repertoire with a wide audience. Her Ph.D. thesis titled "Inventing nothing in art: paradoxes about Isadora Duncan's dancing" (Schwartz-Rémy 2014) is a result of her many years of studying Isadora Duncan's philosophy of movement. In an effort to transmit Duncan's philosophy of movement, she created an amateur dance company that performed Duncan's dance pieces.

Our co-design methodology involved Elisabeth as well as me and my supervisors in all the stages of the design process. During the first year of this Ph.D., due to the COVID-19 pandemic, most of the co-design process took place as Zoom calls and email exchanges. In the following two years, we were able to meet in person to continue our collaboration. In the last year of the Ph.D., I was able, along with my supervisor Sarah Fdili Alaoui, to take dance classes with Elisabeth, to further deepen my kinesthetic understanding of Isadora Duncan's movement philosophy. In the following section, I will describe the first part of the co-design process that took place a bit before my Ph.D. and throughout the first year of my Ph.D. During this first part, Elisabeth was involved in every step of the process, from defining the movement principles to assessing the prototypes that we produced to experimenting with the prototypes in the studio.



3.1.2 Understanding the Duncanian Movement

Prior to the beginning of this Ph.D., Elisabeth was invited to our lab for a day to build an understanding of Duncan’s work. Elisabeth made a presentation and performed examples that represented Duncan’s qualities of “natural movement”. The team then had a long conversation and brainstorming session on possible visualizations of Duncan’s qualities.

Elisabeth explained what the “natural movement” is, as expressed by Isadora Duncan in her autobiography (Duncan 1927) and other writings (Duncan 1928), through 3 main principles.

Fluidity

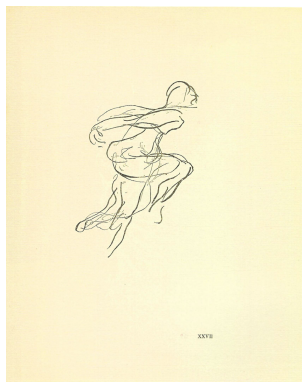
One of the main characteristics of Duncan’s movement is fluidity. The fluidity in Duncan’s philosophy can be described as the perpetual motion of the body, its continuity. “*There is a quality of perpetual oscillation in Duncan’s work*” said Elisabeth. She added: “*This really gives a movement quality that is continuous, perpetual, always picked up by a curve, an 8 shape, a spiral. And so what we could define as a natural movement is a movement which sometimes accelerates, sometimes slows down, in suspension. It lets the momentum work its way, lets this game with gravity work. I think that would be her natural movement.*”

In order to visualise fluidity, Elisabeth suggested to use the metaphor of the ribbon. In fact she declared that Isadora Duncan always danced wearing fluid fabrics such as loose silk dresses as shown in Figure 3.1. Moreover when artists would draw Isadora dancing, their drawing would look like she and her draped clothes are just one entity (Rousier 2005), as shown in Figure 3.2. Elisabeth herself uses loose silk scarves with her students to support their embodiment of the fluid continuous movement in free flow. The metaphor of the scarf was used by Tove Grimstad in her work (Bang et al. 2023) where she co-designed a sonic scarf to support dancers’ embodiment of Duncan qualities. This showcased how the ribbon/scarf/loose fabric imaginary holds central place in Isadora Duncan’s philosophy. Elisabeth also suggested to visualize the ribbon in 3D in order to display the curves and spiraling movements in Duncan’s repertoire.

To visualize this quality, we proposed to use a physical model in the form of ribbons that can freely deform following motion capture data. Such model’s motion should be fluid and continuous while following the dancer’s movements.



Figure 3.1 – Isadora Duncan Dancing (from <https://www.linflux.com/arts-vivants/isadora-duncan-et-la-danse-libre/>)



(a) Artist: Grandjouan, from (Rousier 2005)



(b) Artist: Van Dearing Perrine, from the Collection of Janaea Rose Lyn

Figure 3.2 – Drawings of Isadora by different Artists.

The Solar Plexus

Elisabeth also described how Duncan attempted to find the origin of movement and how she located it near what she refers to as the solar plexus: “*I know only one dance and it is this movement: drawing back your hands to the solar plexus, whereupon an inner force opens up your arms and raises them*” (Duncan 1927). In giving the solar plexus metaphysical overtones and locating it between the breasts, Duncan obviously uses the term in a nontechnical, that is, non-anatomical sense (Layson 1987) and rather in a poetical sense. Elisabeth referred to the solar plexus as “*the location of the reception and distribution of the undulating forces of movement*”.

In order to visualize this characteristic, we proposed to work with geometric representation of a virtual dancer organized around a center located on the chest, which we also call the solar plexus for convenience.



The Wave

Another important element of Duncan’s natural movement that Elisabeth emphasized is that motion should propagate along the dancer’s body like a wave. Duncan writes: “*all movements in Nature seem to me to have as their ground plan the law of wave movement*” (Duncan 1928). Elisabeth emphasized how the wave presents a duality: “*how matter moves and how the energy propagates. The wave involves the asymmetry of opposing forces. The asymmetry of the supports reflects the acceptance of this double polarity in movement*”. The wave organizes movement in such a perpetual undulating rhythm. “*My first idea of movement, of the dance, certainly came from the rhythm of the waves*”

In order to visualize this characteristic, we proposed a model where movement always progresses in a wave from the center to the peripheries of the representation.

In order to follow the philosophy of Duncan’s movement, we decided to model the human body with five ribbons connecting the plexus to the body extremities (hands, feet and head) giving the model a star shape. Using rods instead of a rigid skeleton would support the fact that the dance of Isadora Duncan is unconstrained to one’s body. The rods would also convey the fluidity of the movement better, as rods are not restricted to bend and twist at a fixed set of locations only (the joints of a skeleton). We decided to join the rods to the solar plexus because in Duncan’s philosophy the energy comes from the solar plexus, and it is the root of all movements. Elisabeth also mentions a “star-shaped body” structured around the solar plexus when describing the body when dancing Duncan’s pieces: “[The solar plexus] is a center, and all the body irradiates in succession: the arms, the top of the head down to the neck, the lower back, the legs. A center, movement in successions which gives a construction almost as a starfish. A really flexible starfish.”

3.1.3 Capturing the Dances

The first step for the team was to capture Elisabeth performing Duncans’ pieces using Motion Capture technology. The team collaborated with the MocapLab¹, a private company specialized in Motion capture to record a set of six dances. The six dances that were recorded were Prelude, Moment Musical, Folatrerie, Water study, Mother, Etude Revolutionnaire. All these dances except Water Study were recorded twice. On top of those six dances, we recorded four “lessons” where Elisabeth explained some of the important parts of Isadora Duncan’s philosophy of movement with her body and with words. In order to

¹The MocapLab has already worked on using motion capture in the context of dance in their project with the Paris Opera House (Arcier 2020) and through a collaboration with the urban dance duo the Twins. More information on their website: <https://www.mocaplab.com/fr>

follow Isadora Duncan's will to make sure we had enough precision to retrieve the fluidity of her movements, we chose to record the data at a very high framerate, 100 frames per seconds. The motion capture took place in the MocapLab motion capture room using 36 Vicon cameras (see Figure 3.3). Elisabeth was wearing a motion capture suit, a hat and a pair of shoes where 64 spherical markers were placed on her body (see Figure 4.3 for an illustration of the marker locations).

For the initial design, we worked on three different dances: Prelude, Moment Musical and Folatrerie.



Figure 3.3 – Image of the motion capture process with Elisabeth dancing

3.1.4 Iterative Ribbon Design

Designing the ribbon model took place as an iterative process along with my supervisors, co-authors and Elisabeth. As soon as a new design was achieved we would have discussions with Elisabeth about her perception of the model and would iterate on the model accordingly. Due to the COVID-19 pandemic, most of the iterative design process had to take place virtually through emails and video calls.



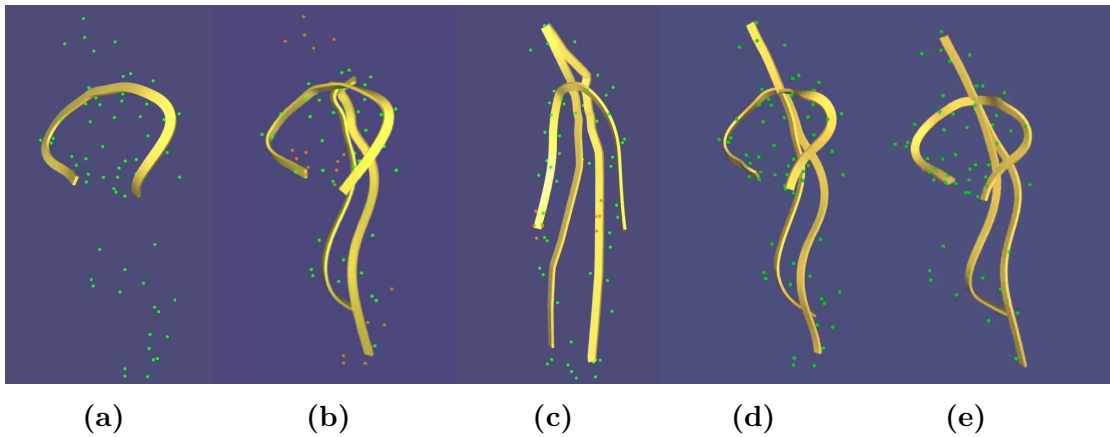


Figure 3.4 – The successive versions of our ribbon model, co-designed through multiple iterations with Elisabeth, the expert Duncanian dancer.

Initial Design of the Model Based on our initial conversation with Elisabeth, that led to our design principals, I proposed a first version of the model, representing the arms of the dancer, taking the form of a straight flexible ribbon going from one hand to the other as shown in Figure 3.4a. The ribbon was computed to follow the motion captured data of Elisabeth performing the dances. Using a ribbon instead of a rigid skeleton would correspond to the fact that the dance of Isadora Duncan is unconstrained to one’s body. This would convey the fluidity of the movement better, as well as the wave propagation, as ribbons are not restricted to bend and twist at a fixed set of locations only (the joints of a skeleton).

We discussed this representation with Elisabeth via emails and a video call. We showed her the ribbon performing Prelude and Moment musical. She thought that the use of the ribbon to model dance movements was coherent with Duncan’s philosophy. She highlighted some of the qualities of the model: *“They make the Duncanian movement more visible and more readable, which lets us have a more precise analysis. We can really see the quality of the gestures, the momentum, the looseness and the suspension, the stretching of time.”* She also thought that the model represented the arms movement in a quite accurate way.

To improve the model, she suggested to create more ribbons representing the limbs, all around the solar plexus. *“As a dancer of Duncan, I can spot the arms’ movement really well in Prelude, beyond the difficulty of the half turns and pivots. It will be amazing when the other ribbons linking the arms to the solar plexus and other parts of the body such as the bust and the head are created. A stylistic Duncanian rendering through this abstraction will become visible.”*

She emphasized the need for a representation with legs, as the interactions between the feet and the ground is essential in Modern dance in general, and more precisely in Duncan’s

dance: “*The question of support needs to be treated, because it is central in dance, thus the idea of creating a ribbon which takes into account the feet. Modern dance in its early ages took a close attention to the extremities*”.

Elisabeth also mentioned the ways in which the ribbon can move and how it conveys the Duncanian movement philosophy: “*The ribbon with three parameters (stretch, twist and bend) also shows the importance of the looseness and of the informal wholeness of Duncan’s dance because from an aesthetic point of view, we are not in an articulated body, formally defined.*” She also expressed the idea to have multiple representations for different dances: “*For Moment Musical, maybe a ribbon from the feet to the torso/head, would that be possible? For Prelude, a ribbon from the feet to the torso, the head, the arms to the hands.*”

First Iterations on the Model Following Elisabeth’s recommendations, we focused on the creation of legs, as Elisabeth emphasized their central role in Modern dance. As suggested by her, we tried 2 different settings: one with one ribbon for the arms and one ribbon per leg, starting at the solar plexus (Figure 3.4b), that we tested on data captured of Elisabeth performing Prelude, and the other in the shape of an A, with one common ribbon for the arms, and one ribbon for each leg-to-head line (Figure 3.4c), that we tested on the data captured of Elisabeth performing Moment Musical.

However, while both those representations brought something interesting to the model, the A shape did not highlight the fact that the solar plexus was the center of movement. Indeed, as Elisabeth explained when referring to the plexus: “*It is a center and all the body irradiates in succession: the arms, the top of the head down to the neck, the lower back, the legs. A center, movement in successions which gives a construction almost like a starfish. A really flexible starfish.*” This also highlighted the fact that the head was a very important part of the body and therefore that it also needed to be represented.

Last Iteration on the Model Taking into account the need to convey the importance of the solar plexus and the mention of a “starfish” shaped body, from where “*an inner force opens up your arms and raises them*”, we broke the arms ribbon into two pieces, one for each arm, added a ribbon for the head and used a ribbon per leg. All ribbons were joined at a common point that we located on the chest of the dancer and were kept connected to each other throughout the dance at this same position on the chest. This fourth version of the model is thus an abstract figure in the shape of a starfish, with five ribbons attached together at the solar plexus, as shown in Figure 3.4d. We then decided to better constrain the movements of the ribbons so that they better follow those of the solar plexus. Indeed, while the ribbons of our previous model could freely rotate around themselves, we decided to fix their orientation at the solar plexus, so as to make it match the solar plexus’s normal,



and let their orientation freely propagate from this point according to the physics of the ribbons. This model is displayed in Figure 3.4e.

We discussed this last version with Elisabeth in person. She still thought that the representation was aligned with Duncan’s philosophy of movement. *“I like the ribbons. I think that with respect to Duncan there is a coherence. I like this physical rendering. To show the continuous movement, the continuous rhythm.”* She also mentions how the ribbons display the characteristics of Duncan’s movement, particularly the “8” shape drawn by the hips and the particular way that the head is moving. *“What I really like is that it gives us to see how the whole body moves. The hips from left to right, the freedom of the head, etc.”* She also mentions that the model shows how the movement comes from the plexus. *“In fact I perceive something really accurate style-wise. These are movements that deploy starting from the center. Yes, that is why I insist on the plexus being the center of movement.”*

Animating Ribbons from Motion Capture Data: Method and Choice of Parameters

In this section we will explain how we animated the ribbons to follow the motion captured data. In practice, the ribbons are modeled as isotropic rods, i.e. have a circular cross-section, which let them equally bend and twist in any direction. However, we *display* them as *flat* ribbons to better visualize their twist. Moreover, we assume that the so-called natural shape of each rod, i.e. its shape at rest or shape with 0 deformation energy, is straight, so as not to favor any particular direction for bending and twisting, while simplifying modeling.

4.1 Input Data

The input data comes from the motion captured session described in Section 3.1.3. During those dances 65 markers were placed on Elisabeth's body in order to track movements as displayed in Figure 4.3. The data that we worked with was then the position (x, y, z) of each marker at each time frame. In this chapter we will denote $s_k = (s_{x_k}, s_{y_k}, s_{z_k})$ the position at current time of marker number k , and denote s_{CLAV} the 3D position of marker named CLAV.

Moreover we were also able to animate the ribbons from skeletal motion captured data, which is a more common way to store motion capture data. To achieve this, we use every 3D position of the joints of the skeleton to be a marker. However the joint position lacks information of the rotation of the bone around its tangential axis. To add that rotation information to the set of markers we add two imaginary marker s_{new1} and s_{new2} associated to each bone. Let s_a and s_b be the extremities of a bone, and v_1 the first vector of the



vector frame associated to the bone. The new imaginary markers are then

$$s_{new1} = \frac{s_a + s_b}{2} + \frac{\|s_a - s_b\|}{2} \frac{v_1}{\|v_1\|}$$

$$s_{new2} = \frac{s_a + s_b}{2} - \frac{\|s_a - s_b\|}{2} \frac{v_1}{\|v_1\|},$$

as shown in Figure 4.1.

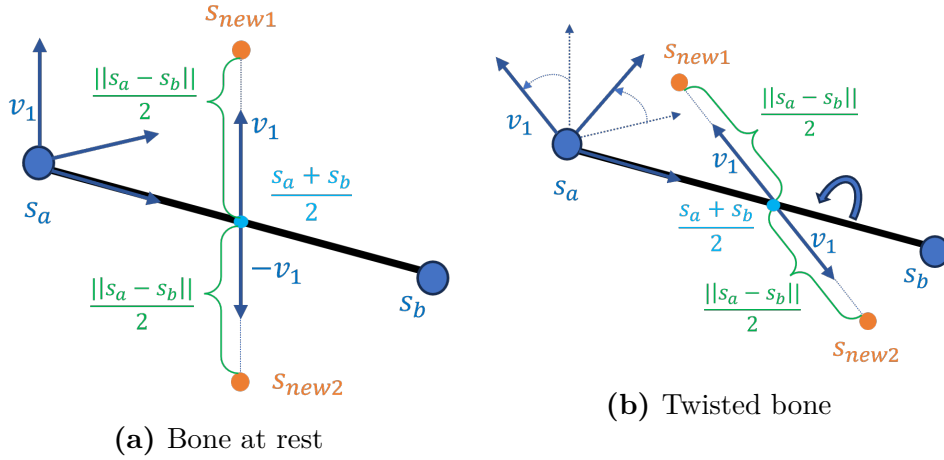


Figure 4.1 – Position of the added markers s_{new1} and s_{new2}

The input data is then a set of K 3D points, whether they come from the position of marker on the dancer’s body or ones that are created from the joint and joints rotations of the skeleton. Figure 4.2 displays the markers coming from the raw motion capture data as well as the marker created from skeletal data, and their respective ribbons.

4.2 Method Overview

We want to model the dancer’s movements using ribbons. For that purpose we decided to use a discrete model of elastic rods as described in (Bergou et al. 2008). We want that ribbon to follow the dancer’s movement. In order to achieve this, we will “connect” the ribbon to the different markers using springs. We want to be able to determine the position of the ribbon and its orientation at each time frame. To do so we will minimize the total energy of the physical model which combines 2 types of energies: the energy associated to the ribbon’s deformation (twist, bend and stretch) and the energy associated with the springs that were attached to the ribbon.

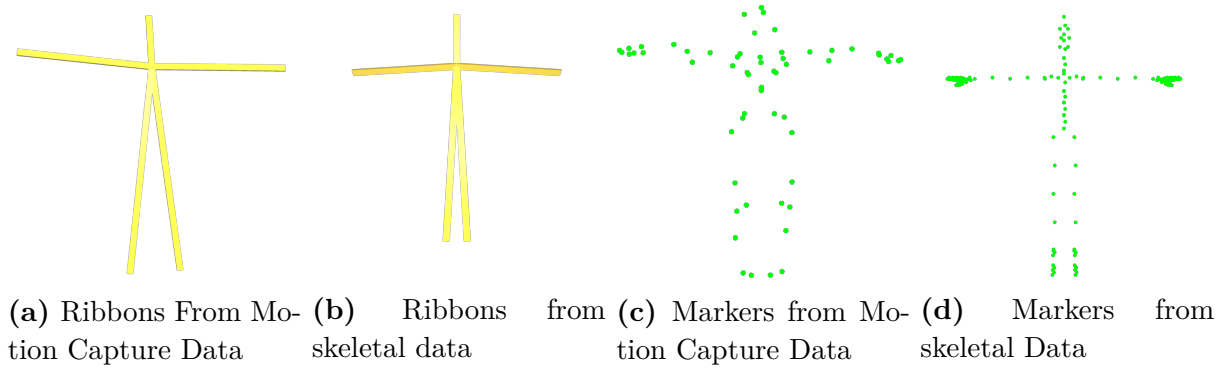


Figure 4.2 – Ribbons and Markers from skeletal data and raw motion capture data

4.3 Discrete Elastic Rod Notions

In the following section the different notations that are useful for the description of the physical model of (Bergou et al. 2008) are introduced. Then the energies associated to a discrete elastic rod are developed and new energies are introduced in order for the ribbon to follow the data.

A discrete elastic rod Γ as defined in (Bergou et al. 2008) is composed of a centerline and a set of frames. The centerline is made of a set of vertices $(x_i)_{i \in \llbracket 0, n+1 \rrbracket}$. From these vertices can be defined the edges $e^i = x_{i+1} - x_i$, $i \in \llbracket 0, n \rrbracket$, see Figure 4.4. The sets of frame $M^i = \{t^i, m_1^i, m_2^i\}$, (where t^i is the tangential vector, m_1^i is orthogonal to t^i and define the orientation of the rod and $m_2^i = t^i \times m_1^i$) are adapted to the centerline curve, that is $t^i = e^i / \|e^i\|$. This set of frames is used to track the rotation of the rod's cross-section and are called material frames.

4.3.1 Bishop Frame Versus Material Frame

In order to track the twist of the rod, we need a frame that will serve as a reference. Indeed when one vertex x_i of the centerline is moved, then the tangent which depend on it e^i and e^{i+1} are impacted which leads to a change of frame since the frames are adapted. The Bishop frame $\{t, u, v\}$ is defined as the adapted frame that is of zero twist and is used as a reference frame in this setting. Therefore the material frame (the one associated to the rod) can be expressed with respect to the Bishop frame via the angle θ as displayed in 4.5 through these equations:

$$m_1 = \cos(\theta)u + \sin(\theta)v, \quad m_2 = -\sin(\theta)u + \cos(\theta)v.$$



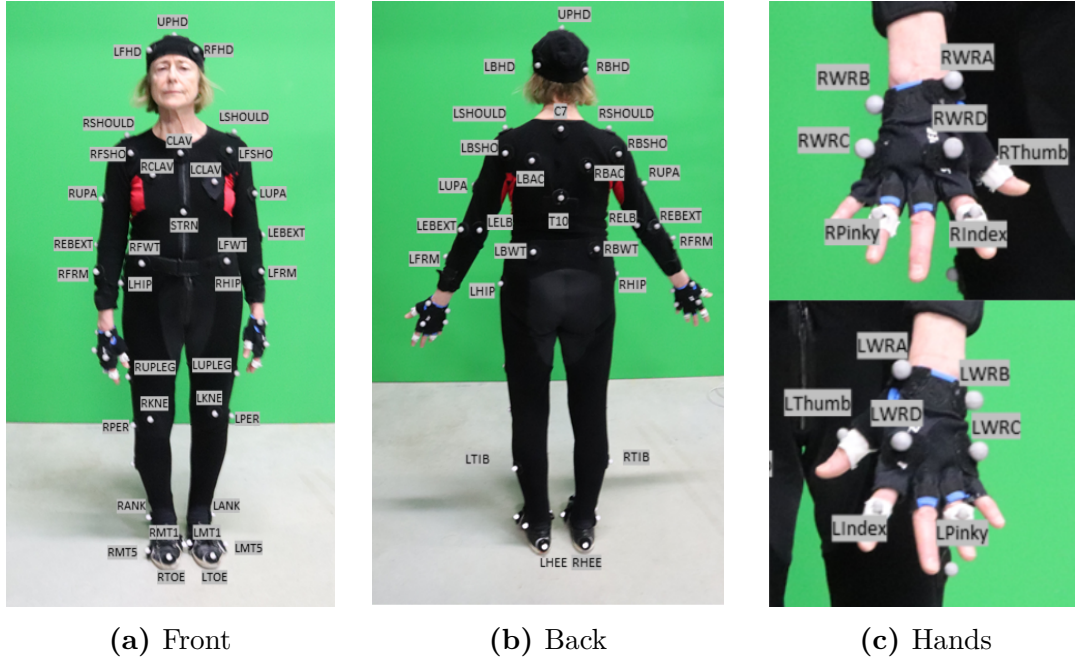


Figure 4.3 – Positions of the sensors on the dancer's body

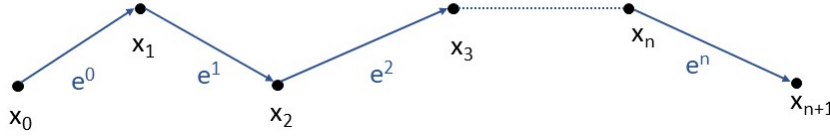


Figure 4.4 – Diagram displaying indexing of vertices and edges of the centerline

Since the Bishop frame is defined at all times and positions on the centerline, the material can be only expressed with respect to the Bishop frame through its angle of rotation θ around the axis led by the tangential vector t .

4.3.2 Parallel Transport

The notion of parallel transport is essential in the discrete elastic rod framework for it enables to define the Bishop frame at all time τ and all position i on the centerline. To parallel transport a vector a to a vector b one performs the rotation of minimum angle to be able to align a to b . That is, performing a rotation of axis $a \times b$ and of angle ϕ such that $a \cdot b = \|a\| \|b\| \cos(\phi)$.

To define the Bishop frame at all position in the centerline, it is enough to have an initial Bishop frame at edge $i = 0$. To obtain the Bishop frames for the whole rod one just parallel

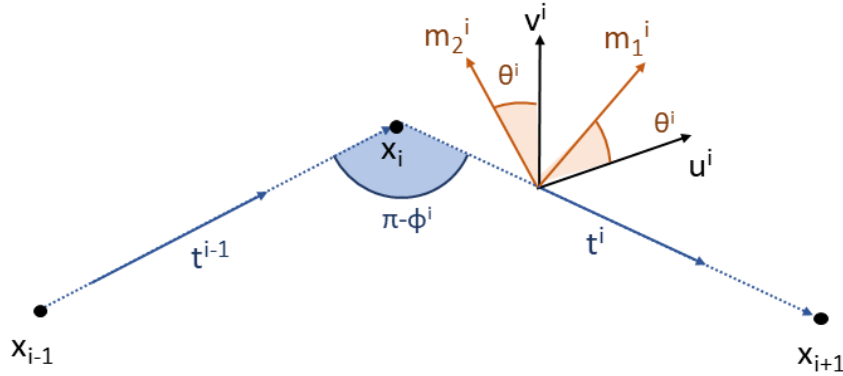


Figure 4.5 – Diagram displaying relations between material frame and Bishop frame

transports consecutively of the tangential vectors $i - 1$ to vector i . If we denote the parallel transport to go from t^{i-1} to t^i P^i this gives the equation

$$P^i(t^{i-1}) = t^i, \quad P^i(t^{i-1} \times t^i) = t^{i-1} \times t^i.$$

In order to define the Bishop frame at all edges, we parallel transport the frame numbered $i - 1$ to the frame numbered i using P^i :

$$P^i(t^{i-1}) = t^i, \quad P^i(u^{i-1}) = u^i, \quad v^i = t^i \times u^i.$$

To obtain the Bishop frame at another time step, we parallel transport the initial Bishop frame to the initial tangential vector at the desired time and then parallel transport it along the tangential vectors.

4.3.3 Integrated and Pointwise Quantities

In the next section we will talk about the different energies that govern the discrete elastic rod. In the continuous setting, when evaluating an energy, we often consider certain quantities pointwise and to obtain the energy we integrate over the centerline. In the discrete setting we will also make the difference between pointwise quantities and integrated quantities. To convert an integrated quantity to a pointwise one, we just divide by the length of the domain of integration. In the discrete case, this is done by dividing by the length $D = l_i/2 = \frac{\|e^{i-1}\| + \|e^i\|}{2}$ which corresponds to the Voronoi region associated with the vertex x_i .

4.4 The Different Energies

In the following section we will define the different elastic energies which govern the physical simulation of the discrete elastic rod and add the energies needed to obtain a ribbon that follows the data.

4.4.1 Elastic Rods Energies

In the elastic rods framework 3 energies are used: bending, twisting and stretching. The total energy is then $E(\Gamma) = E_{\text{bend}}(\Gamma) + E_{\text{twist}}(\Gamma) + E_{\text{stretch}}(\Gamma)$. In each section we will describe each energy for a single element (edge or vertex), and give the value of the energy for the entire rod. Throughout the manuscript, we will denote \bar{a} the value at rest of a , corresponding to the value of a when no forces are applied on the system.

4.4.1.1 Stretching Energy

The first energy introduced in the elastic rod's framework is a stretching energy which enables to enforce the stiffness of the rod's centerline. It is represented mechanically by a spring connected to each extremity of an edge. The stretch energy associated with one edge e^i is expressed as:

$$E_{\text{stretch}}(e_i) = \frac{1}{2} \frac{\eta(\|\bar{e}^i\| - \|e^i\|)^2}{\|\bar{e}^i\|},$$

where η is the coefficient which states how much the rod can stretch. In our setting we consider that η is the same for all edges of the rod, meaning the ribbons have the same stiffness throughout their centerline. The total energy over the rod Γ is obtained by summing over all $n + 1$ edges of the rod:

$$E_{\text{stretch}}(\Gamma) = \frac{1}{2} \sum_{i=0}^n \frac{\eta(\|\bar{e}^i\| - \|e^i\|)^2}{\|\bar{e}^i\|}.$$

We can point out that this energy depends on the position of the vertices $(x_i)_{i \in [0, n+1]}$.

4.4.1.2 Twisting Energy

In the continuous setting, the twist m of a frame is defined by $m = m'_1 \cdot m_2$. The twist energy is then

$$E_{\text{twist}}(\Gamma) = \frac{1}{2} \int_0^L \beta m^2 ds,$$

where β is a coefficient which states how likely the rod is to twist, m'_1 is the derivative of m_1 with respect to the arc length parametrization of the rod, and L the total length of the rod. We want to express this energy with respect to θ because it will be much easier to express the material frame with respect to the Bishop frame. We recall the relationship between the material frame and the Bishop frame $m_1 = \cos(\theta)u + \sin(\theta)v$, $m_2 = -\sin(\theta)u + \cos(\theta)v$. This gives the value of the twist with respect to theta:

$$\begin{aligned} m &= m'_1 m_2 = (-\theta' \sin(\theta)u - \theta' \cos(\theta)v) \cdot (-\sin(\theta)u + \cos(\theta)v) \\ &= \theta' (\cos(\theta)^2 + \sin(\theta)^2) \\ &= \theta'. \end{aligned}$$

The energy is then:

$$E_{\text{twist}}(\Gamma) = \frac{1}{2} \int_0^L \beta (\theta')^2 ds.$$

In the discrete setting, by using a first order approximation of the pointwise quantity $m_i = \theta'_i$ ($\theta'_i \approx \frac{\theta^i - \theta^{i-1}}{\bar{l}_i}$) this point-wise twisting energy translates into

$$E_{\text{twist}}(\theta^{i-1}, \theta^i) = \frac{1}{2} \beta m_i^2 = \frac{1}{2} \beta \left(\frac{\theta^i - \theta^{i-1}}{\bar{l}_i} \right)^2.$$

To obtain the total twisting energy, we sum over all n consecutive pairs of frames:

$$E_{\text{twist}}(\Gamma) = \frac{1}{2} \sum_{i=1}^n \beta (m_i)^2 \bar{l}_i = \frac{1}{2} \sum_{i=1}^n \frac{\beta (\theta^i - \theta^{i-1})^2}{\bar{l}_i}.$$

4.4.1.3 Bending Energy

In the continuous setting, the rod's curvature for a straight isotropic rod is defined as the curvature (normal) vector $\kappa = t'$ (in the case of arc length). This leads to the following expression of the energy associated to bending:

$$E_{\text{bend}}(\Gamma) = \frac{1}{2} \int_0^1 (\alpha(\kappa)^2) ds,$$

where α defines how much the rod is likely to bend (the higher α , the less likely the rod is to bend).



In the discrete setting, we first need to define the curvature binormal vector $(\kappa b)_i$ as the vector normal to e^{i-1} and e^i of amplitude $2 \tan \phi/2$ (where ϕ is the angle between e^{i-1} and e^i as displayed in 4.5):

$$\kappa b_i = \frac{2e^{i-1} \times e^i}{\|\bar{e}^{i-1}\| \|\bar{e}^i\| + e^{i-1} \cdot e^i},$$

where $a \times b$ is the cross product between a and b . The energy for bending is then

$$E_{\text{bend}}(\Gamma) = \sum_{i=1}^n \frac{\alpha(\kappa b_i)^2}{\bar{l}_i},$$

In our specific case, we will only use the straight isotropic case because we do not want the rod to be more likely to bend in a certain direction. Indeed the rods are animated to follow the markers position, and so the bio-mechanical constraints of the body, i.e. the physiological limits of each joints rotation, are contained in the markers positions.

4.4.2 Data Energies

In this section, we introduce new energies which will enable the ribbon to follow the data and therefore for it to match the dancer's movement closely. We will introduce two kinds of energies: the markers position energy $E_{\text{linear}}(\Gamma)$ and the angular position energy $E_{\text{angular}}(\Gamma)$. Therefore the total energy of our ribbon will become

$$E(\Gamma) = E_{\text{bend}}(\Gamma) + E_{\text{twist}}(\Gamma) + E_{\text{stretch}}(\Gamma) + E_{\text{linear}}(\Gamma) + E_{\text{angular}}(\Gamma).$$

This energy is introduced so that the centerline of the ribbon follows the data (i.e. marker's positions). For that purpose we will introduce springs between each marker and its projection onto the ribbon.

4.4.2.1 Linear Spring Associated with Data

This energy is introduced so that the rod is following the movements of the dancer that is contained in the position of the motion capture marker. To define this energy we first connect a spring between each marker s_k and its closest edge e^{i_k} on the centerline by projecting s_k onto the centerline at time $\tau = 0$ as shown in Figure 4.6. This projection gives a point \bar{c}_k . \bar{c}_k belongs to the edge e_{i_k} as displayed in Figure 4.6. Now we want to express c_i with respects to the two vertices of the edge x_{i_k+1} and x_{i_k} . For that purpose we use barycentric coordinates $c_k = y_k x_{i_k} + (1 - y_k) x_{i_k+1}$ with $y_k \in [0, 1]$. The spring's rest state is evaluated at time $\tau = 0$. Let us denote z^k the vector such that $z^k = s_k - c_k$ the

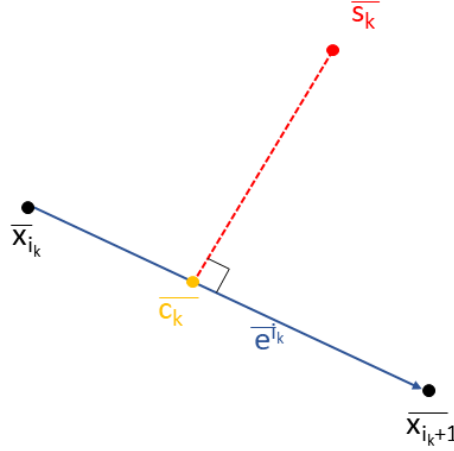


Figure 4.6 – Example of a linear spring connecting a marker to an edge

vector between the marker and its projection, and \bar{z}^k its value at rest. The energy of the spring connecting c_k to s_k is then:

$$E_{\text{linear}}(s_k) = \frac{1}{2}a \frac{(\|\bar{z}^k\| - \|z^k\|)^2}{\|\bar{z}^k\|},$$

where a is the rigidity of the spring. This energy only depends on x_{i_k} and x_{i_k+1} . If the marker is located on the edge at rest, which means $\|\bar{z}^k\| = 0$, we set the energy to be:

$$E_{\text{linear}}(s_k) = \frac{1}{2}a\|z^k\|^2,$$

The total energy along the rod is then obtained by summing over all K markers associated with the rod:

$$E_{\text{linear}}(\Gamma) = \sum_{k=1}^K E_{\text{linear}}(s_k).$$

4.4.2.2 Angular Spring Associated with Data

The linear energy enables the rod to follow the position of the associated markers through time. However, it does not impact the material frame and thus does not allow to track the rotation of the markers around the body. Therefore, we introduce an angular spring between the marker and the rod. The goal is for the angular difference between the marker and its associated edge to remain constant for a change of angle to impact the position of the material frame. For that, we used the previously defined vector $z^k = s_k - c_k$. We want



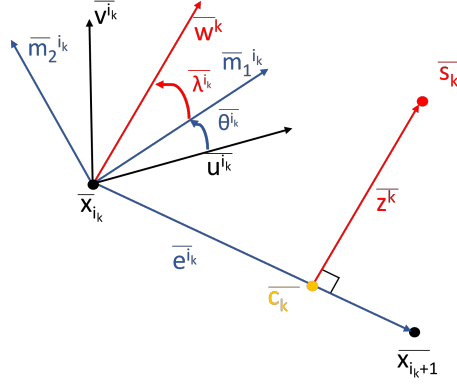


Figure 4.7 – Example of an angular spring connecting a sensor to an edge

to track the twisting angle, that is, we want to evaluate the rotation around the tangent t^{i_k} .

At rest state, since \bar{c}_k is defined as the projection of \bar{s}_k onto the centerline, we have $\bar{t}^{i_k} \cdot \bar{z}^k = 0$. However, through time, as the marker s_k moves in space and c_k is still defined using the initial barycentric coordinates, there is no guarantee that orthogonality is maintained.

To ensure we are only taking into account rotation angles related to non-tangential components, we first project the normalized z^k vector on the plane defined by the non-tangential vectors of the reference frame u^{i_k} and v^{i_k} . This projection yields a new vector $w^k = (\frac{z^k}{\|z^k\|} \cdot u^{i_k})u^{i_k} + (\frac{z^k}{\|z^k\|} \cdot v^{i_k})v^{i_k}$. Then we denote λ^{i_k} the minimum angle required to move $m_1^{i_k}$ (the material frame) to w^k see Figure 4.7. We want the material frame (and therefore θ) to move so that the angle (λ^{i_k}) between the material frame and the marker s_k remains the same as it is at rest state. The energy for this angular spring associated with the edge e^{i_k} is

$$E_{\text{angular}}(e^{i_k}) = \frac{1}{2}q(\bar{\lambda}^{i_k} - \lambda^{i_k})^2,$$

where q is the rigidity of the spring. In the case where $\|z^k\| = 0$, we set $\lambda^{i_k} = 0$.

We want to express these angles with respect to θ . We denote $\widehat{u^{i_k} z^k}$ the angle between u^{i_k} and z^k . We then have $\lambda^{i_k} = \widehat{u^{i_k} z^k} - \theta^{i_k}$. The energy can then be written as

$$E_{\text{angular}}(e^{i_k}) = q(\widehat{u^{i_k} z^k} - \bar{\theta}^{i_k} - \widehat{u^{i_k} z^k} + \theta^{i_k})^2.$$

We notice that this energy depends on θ^i .

To obtain the total angular spring energy for the rod, we sum over all K markers associated

to the rod:

$$E_{\text{angular}}(\Gamma) = \frac{1}{2} \sum_{k=1}^K q(\overline{\lambda^{i_k}} - \lambda^{i_k})^2,$$

These different energies offer an easy way to represent the rod. Indeed, they all explicitly depend on the position of the centerline x_i or the angle between the Bishop frame and the material frame θ^i . This separation between the two sets of variables will be helpful in the minimization process because we can treat the minimization as a two-step process, minimizing the energy first with respect to x_i and then to θ_i .

4.5 Generating the Initial Ribbon

4.5.1 Rest Shape and Initial Shape

We define the rest shape of the rods by using the motion-captured data when the dancer takes a T-pose. A T-pose is a specific pose that is commonly used in 3D computer graphics and animation. It is called a T-pose because the person or character resembles the letter “T” when viewed from up front, with their arms extended straight out to the sides and their feet together. While this pose may not be the most “natural” in the sense Isadora Duncan uses this word (e.g., when referring to the “natural movement”), it is a pose most mocap systems ask the user to take to calibrate the system, and is present at the beginning of all the recordings. Therefore, using this pose allows us to ensure that our rods’ rest shape is consistent across all animations while exhibiting low bending of the limbs, which is coherent with our assumption for the rods to be straight at rest. Since all our recordings start with the T-pose, the initial rod (at time $\tau = 0$) is also the rod at rest state.

4.5.2 Rest Shapes of Rods’ Centerlines

As stated in Section 4.4, the discrete elastic rods requires a rest state for the rod. We recall that rods are straight at rest, which means that the centerline at rest state can be described as a 3D segment. Let us denote s_{plexus} the 3D position of the solar plexus. In our case we define it as the midpoint between the markers named CLAV and C7 (see Figure 4.3), i.e.

$$s_{\text{plexus}} = \frac{s_{\text{CLAV}} + s_{\text{C7}}}{2}. \quad (4.1)$$

We process each limb (arms and legs) and the head separately and create a rod for each. We first manually group all markers to their corresponding limb (see Figure 4.10a). Figure 4.8



shows which set of markers are associated with each limb. To define the direction of the centerline, we perform Principal Component Analysis (F.R.S. 1901) on the set of the 3D position of each marker (see Appendix A.2 for more details). Let v_0 be the eigenvector with the highest absolute eigenvalue (the most important direction given by PCA). We align v_0 to $\overline{s_{\text{plexus}}}$ to define the direction of the initial centerline (Figure 4.10b). We then enforce the constraint $\overline{x_0} = \overline{s_{\text{plexus}}}$ (Figure 4.10c), to ensure that all the initial ribbons are joined at the solar plexus. In order to define the end point of the 3D segment that is the rod's centerline, we project all the associated markers onto the ray starting at the solar plexus and directed by v_0 (Figure 4.10d). We then define the segment's end point as the furthest projection from the marker (Figure 4.10e). Figure 4.9 displays the resulting centerline for each limb in the case of our motion-captured data.

The 3D segment is discretized according to the desired number of edges. We decided to have a uniform discretization, that is $\forall i \in \llbracket 0, n \rrbracket, \|\overline{e^i}\| = \frac{\|\overline{x_{n+1}} - \overline{x_0}\|}{n+2}$.

4.5.3 Defining the Bishop and Material Frame at Rest

Since we process each limb group separately, there is no guarantee that the obtained centerlines pass through a common plane, and, in practice, the arms are indeed slightly tilted forward (as shown in Figure 4.11b). As we still want the ribbons to be oriented consistently, we rotate them around their respective centerlines so that their normals are as close as possible to a common vector, chosen to be the normal of the solar plexus. To find the Bishop that is as close as possible to the orientation of the solar plexus, we first denote p the orientation of the solar plexus, defined as the normal vector to the plane defined by RCLAV, LCLAV, and CLAV (see Figure 4.3):

$$p = (s_{RCLAV} - s_{LCLAV}) \times (s_{LCLAV} - s_{CLAV}).$$

Since it is a candidate to be a Bishop frame, $\overline{u^0} \cdot \overline{e^0} = 0$, which means $\overline{u^0}$ belongs to the orthogonal plane to $\overline{e^0}$. Let a and b be an orthonormal basis defining this tangential plane. Then the closest v^0 candidate is the projection of the plexus orientation p on the orthogonal plane, that is

$$\overline{u^0} = \left(\frac{\overline{p}}{\|\overline{p}\|} \cdot a \right) a + \left(\frac{\overline{p}}{\|\overline{p}\|} \cdot b \right) b.$$

The last component of the basis is then $v^0 = t^0 \times u^0$. The rest of the Bishop frames are then defined by parallel transporting $\{t^0, \overline{u^0}, \overline{v^0}\}$ along the centerline. In this particular case, since all the tangential vectors are co-linear because the centerline is a 3D segment, we have $\forall i \in \llbracket 0, n \rrbracket, \{t^0, \overline{u^0}, \overline{v^0}\} = \{t^i, \overline{u^i}, \overline{v^i}\}$. Lastly, we define the initial material frame to be the same as the initial Bishop frame, leading to the constraint $\forall i \in \llbracket 0, n \rrbracket, \overline{\theta^i} = 0$.

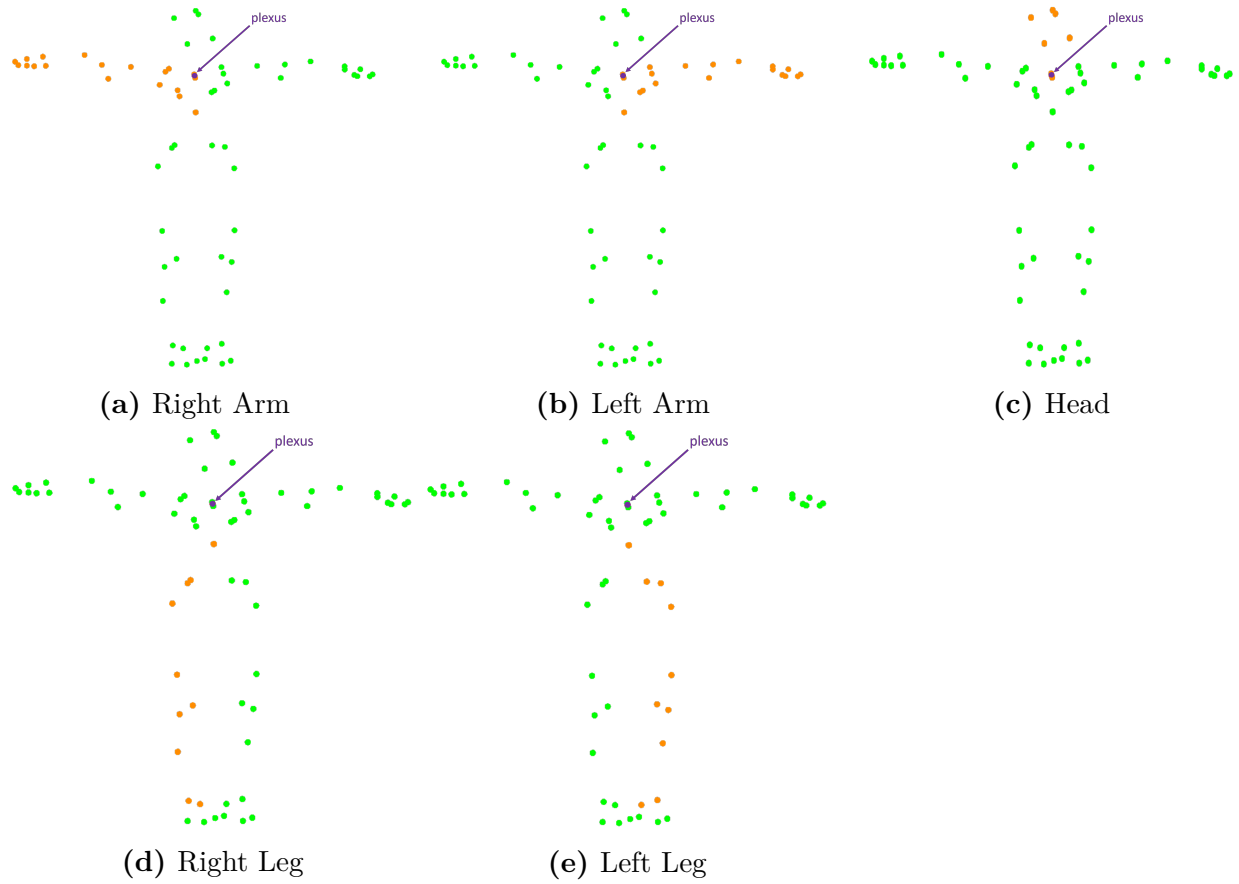


Figure 4.8 – Each marker group for each limb : green not used, orange is used, purple is plexus position

```

input : Set of markers
output: Initial ribbon
for each limb do
    Manually group markers (Figure 4.10a);
    Perform PCA on the set of markers(Figure 4.10b);
    Align  $x_0$  to  $s_{plexus}$  (Figure 4.10c);
    Project all makers on the centerline (Figure 4.10d);
    Set  $x_{n+1}$  as the furthest projection (Figure 4.10e);
    Set uniform discretization of the centerline;
    Define all Bishop frames as close as possible to the plexus orientation;
    Initialize material frames equal to the Bishop frame ( $\theta^i = 0$ );
end

```

Algorithm 1: Generation of the initial ribbons



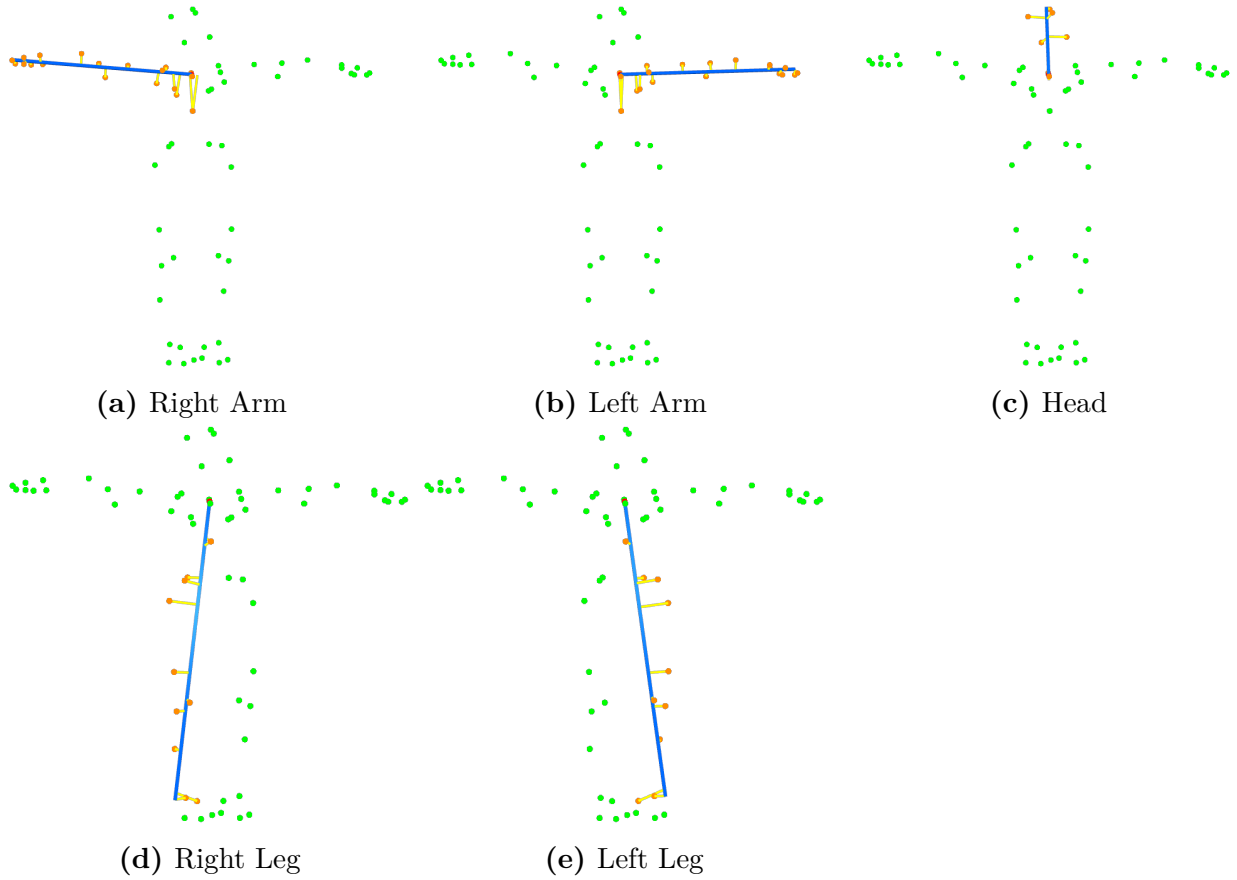


Figure 4.9 – Each initial centerline. Green not used, orange is used, red is plexus position, yellow are the segments between the markers and the centerline

The 5 resulting initial ribbons are shown in Figure 4.11.

4.6 Procedure to Animate the Rod

We consider that at each time frame, the ribbon is at a state of equilibrium, which translates to the energy function reaching a minimum. This lets us perform optimization on the energy function, i.e. at each time step we want to find the optimal ribbon which minimizes its total energy.

Since we decide to have a straight isotropic rod, each energy either depends on the position of centerline x_i or on the angle of the material frame θ^i . We recall that the optimization problem is

$$\min_{\Gamma} E(\Gamma) = \min_{\Gamma} E_{\text{bend}}(\Gamma) + E_{\text{twist}}(\Gamma) + E_{\text{stretch}}(\Gamma) + E_{\text{linear}}(\Gamma) + E_{\text{angular}}(\Gamma).$$

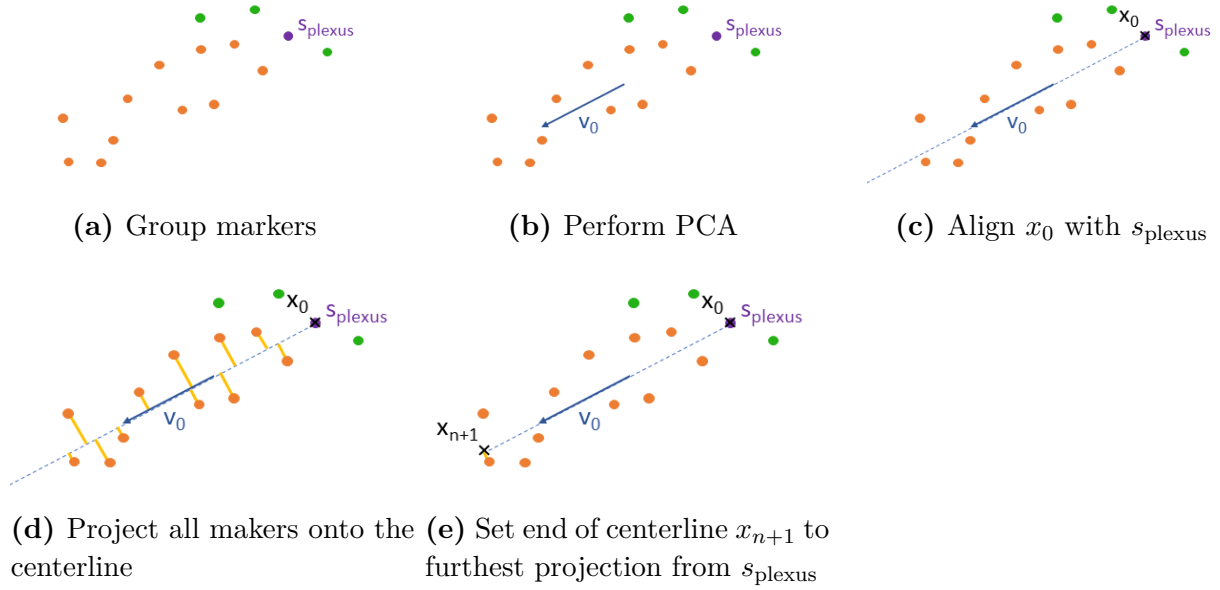


Figure 4.10 – Steps to generate initial centerline

We know that $E_{\text{bend}}(\Gamma)$, $E_{\text{stretch}}(\Gamma)$ and $E_{\text{linear}}(\Gamma)$ depend *only* on the position of the centerline whereas $E_{\text{twist}}(\Gamma)$ and $E_{\text{angular}}(\Gamma)$ depends on the angles θ^i . This lets me treat the optimization of the two sets of variables *almost* independently. Since the Bishop frame is necessary to evaluate the angular spring energy and this depends on the centerline position (because it is adapted), we first find the optimal centerline position and then we find the optimal position of the material frame as shown in Algorithm 2. The variables for the first optimization problem are the vertices x_i and the variables for the second problem are the θ^i .

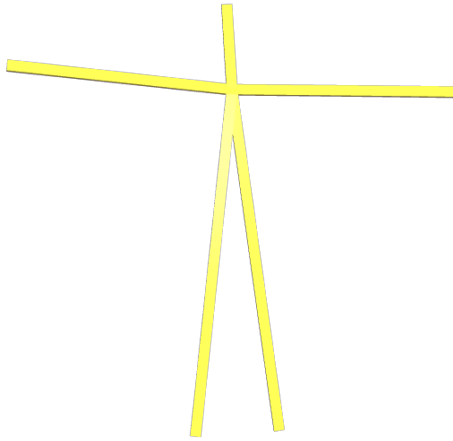
In order to solve the optimization problem we used a Newton's method from the Ipopt library (Wächter et al. 2006). To make the optimization faster, we warm start the Newton's method using the value corresponding to the solution corresponding to the previous time frame. Finally, each rod is treated as an independent problem.

In the case of the 5 flexible ribbons being linked together at the solar plexus, to enforce that constraint on the we set on each ribbon the constraint $\forall \tau, x_0 = s_{\text{plexus}}$. To have a common orientations of the plexus for the 5 different ribbons, we set each first component of the Bishop frame u^0 as the projection of the plexus orientation p onto the tangential plane to t^0 :

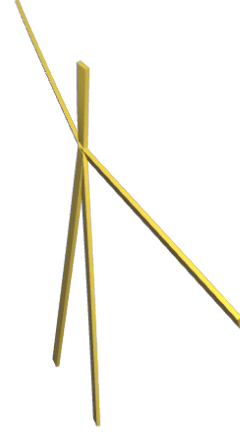
$$u^0 = \left(\frac{p}{\|p\|} \cdot a \right) a + \left(\frac{p}{\|p\|} \cdot b \right) b.$$

where a and b form an orthonormal basis of the tangential plane to t^0 .

As both optimisation problems are gradient based, there is a need to evaluate the gradient



(a) Initial ribbons from up front



(b) Initial ribbons from the side

Figure 4.11 – The generated initial ribbons for the T pose

and the hessian of the energy function $E(\Gamma)$. We computed those using the computer algebra software Mapple (Maplesoft, a division of Waterloo Maple Inc.. 2019).

```

input : Set of markers
output: Animated ribbon
Create initial ribbon;
Generate rest state values;
for each time frame do
    Find optimum  $(x_i)_{i \in \llbracket 0, n+1 \rrbracket}$ ;
    Set centerline;
    Set Bishop frames;
    Find optimal  $(\theta^i)_{i \in \llbracket 0, n \rrbracket}$ ;
    Set material frames;
end

```

Algorithm 2: Simulation steps

4.7 Implementation

I implemented this method within a framework developed in the ANIMA team at Inria which is based on Ipopt (Wächter et al. 2006) for the optimization, Eigen (Guennebaud et al. 2010) for linear algebra and libigl for visualization (Jacobson et al. 2018). This framework enabled to minimize a physical system and visualize the result. I first implemented a

parser that enabled me to read the motion capture files provided by the Mocaplab which were .trc files. I then implemented all of the energies mentioned in Section 4.4 and I set up the optimization problems defined in Algorithm 2. I also generated all the geometry that is used in order to render the ribbon and the markers.

4.8 Different Discretizations of the Ribbon

We first discuss the number of edges that are necessary per ribbon. In Figure 4.12, we show the optimal ribbons for 8 different numbers of edges. Visually, we can see that when the ribbons have 25 edges or more, the discretization does not impact the smoothness of the ribbon and its shape.

Following (Charrondière 2021), we considered that a reasonable number of segments per ribbon is when the Hausdorff distance $d_{Hausdorff}$ between the discretized ribbon Γ and the continuous ribbon $\Gamma_{\text{continuous}}$ is $\frac{1}{1000}$ of the total length of the ribbon L :

$$d_{\text{Hausdorff}}(\Gamma, \Gamma_{\text{continuous}}) < \frac{L}{1000} \quad (4.2)$$

The Hausdorff distance defines the distance between two sets (see Appendix A.4 for more details). In this scenario, there is no way of computing the continuous ribbon to compare it to the discretized ones. Therefore, we consider a ribbon with 1000 segments the “*almost continuous*” ribbon.

To be able to find the best number of segments of the ribbons numerically, we computed the Hausdorff distance of 40 sets of 5 ribbons with discretization between 5 and 200 segments on the Prelude dance (see Figure 4.13). Since we are dealing with animation data, we have 8205 time frames, which means 8205 states to compare. We, therefore, plotted first the maximum Hausdorff distance over all time frames (see Figure 4.13a).

In practice, we plotted the Hausdorff distance divided by the total length of the ribbon $d_{\text{Hausdorff}}(\Gamma, \Gamma_{\text{continuous}})/L$. Therefore, the constraint defined in Equation 4.8 becomes:

$$\frac{d_{\text{Hausdorff}}(\Gamma, \Gamma_{\text{continuous}})}{L} < \frac{1}{1000} = 10^{-3} \quad (4.3)$$

This enables to look for the same value of the distance on the graph for each ribbon.

When looking at the maximum we can see that there is a tendency of the distance to decrease when the number of segments increases. However there are multiple moments where increasing the number of segments can actually increase the Hausdorff distance. This is due to the fact that we are looking at the maximum Hausdorff over all time frames.



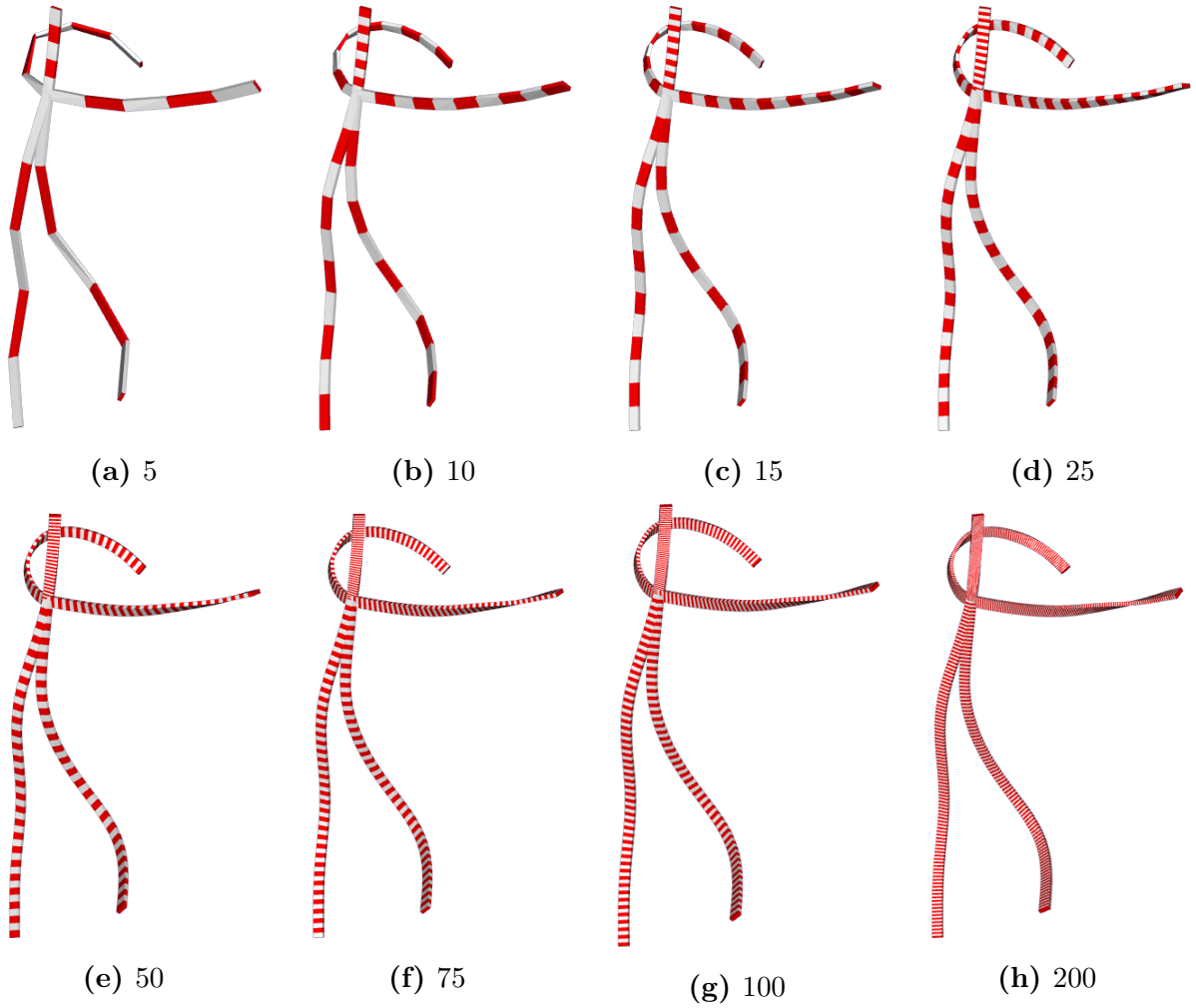
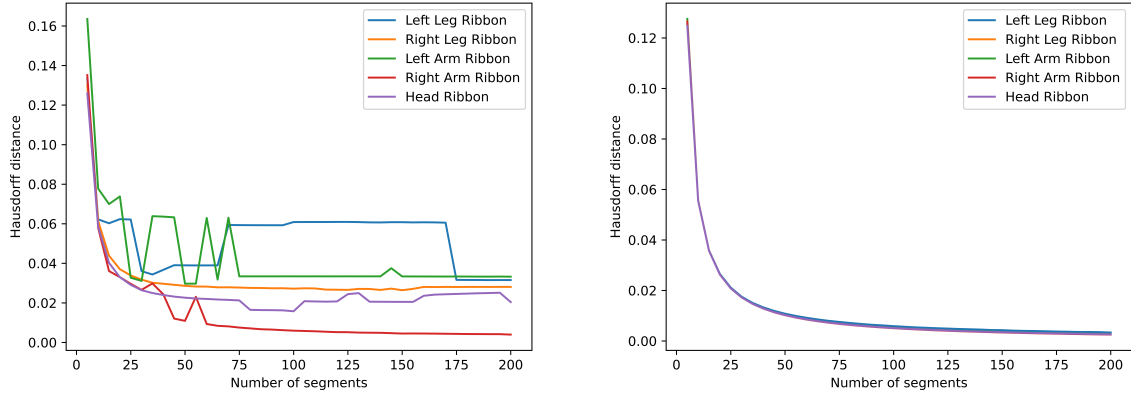


Figure 4.12 – Resulting ribbons for different number of segment per ribbons. Each white or red part represents a segment.

In fact the maximum is reached mostly at the same time frames, and it is significantly higher than the value for the rest of the time frames. One supposition is that the high number of segments for the almost continuous ribbon creates an ill posed optimisation problem and causes the simulation have multiple optima close to one another and therefore the simulation to jump between each.

To avoid this issue we look at the average over all time frames (see Figure 4.13b). We can see that increasing the number of segments always lowers the average Hausdorff distance. However the goal of 10^{-3} is not reached even by 200 segments (the value for each limb is 2×10^{-3}). This can be due again to the instability of the almost continuous ribbon and the high peaks increasing the mean value of the Hausdorff distance. In practice, for the first experiments (see Section 5.2) we have settled for 100 segments per ribbons. This value



(a) Maximum Hausdorff distance over all time frame (b) Mean Hausdorff distance over all time frame

Figure 4.13 – Hausdorff distance between ribbons with different discretization and an “almost continuous” ribbon (in this case with a 1000 edges)

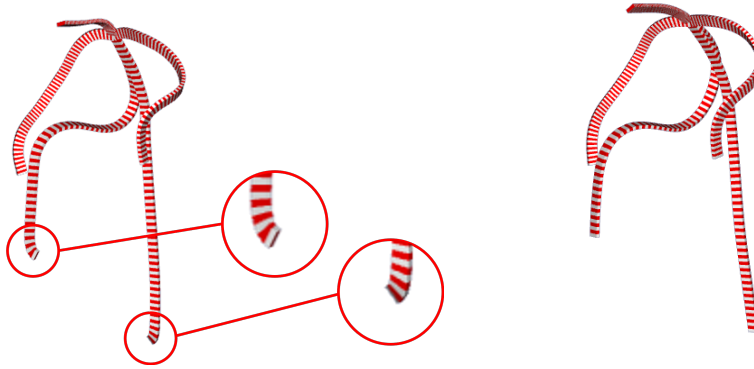
guaranties a decent value of the average Hausdorff distance (3.5×10^{-3}) while having a low enough number of segments that the rendering in the Hololens headset can take place in real time. Indeed since we are working at a high frame rate to keep the animation smooth, increasing the number of segments of the ribbons increases the number of triangles to render per time frame. If the number of triangles is too high to be rendered in time, it can cause the animation to lag, and therefore we lose the fluidity of the movement. For the second experiment (see Section 7), the scene contains more ribbons (which means more triangles to render), and the number of segments were decreasing to the animation from lagging.

4.9 Choice of the Markers

The choice of markers was made through trial and error. The first intuition was to use as many makers as possible that were related to a limb, so as to keep as much information about the recorded dance as possible, and removing markers along the way if problems were encountered.

When using all the markers, we encountered a problem with the feet, as shown in Figure 4.14. The feet kept bending to a high extreme throughout the animations, as shown in Figure 4.14a. This high level of bending around the feet/ankle area is not desirable because the feet and ankle do not bend that far when the feet touch the ground. This issue is caused by considering the markers located on the feet while not having enough segments





(a) Artefact present on the feet when taking into account all markers (b) Resulting ribbons after removing foot markers

Figure 4.14 – Resulting Ribbons showing before and after removing foot markers

to satisfy the movement of the toes' articulation. This leads to the ribbon bending at extreme angles to try to satisfy the linear data energy constraint due to the movement of the marker located on the articulation. Removing the feet markers (RMT1, RMT5, RTOE and RHEE for the right leg ribbon, LMT1, LMT5, LTOE and LHEE for the left leg ribbon) would lower the constraints and keep a straighter ribbon. In practice, removing those markers fixes the problem, as displayed in Figure 4.14b.

4.10 The Role of each Energy

In this section we will discuss the role of the different types of energies on the model and describe how we end up choosing each energies coefficient.

4.10.1 Role of the Stretch Energy

We first discuss the role of the stretch energy. This energy ensures that the rod's length remains close to its initial value (the higher the stretching coefficient, the more inextensible the rod is going to be).

During the optimization process, when satisfying the linear energy constraint, compression and bending can concur when two markers get closer. That means that both directions (choosing the edge of the rod to compress or having the edges to bend) are numerically correct. To avoid over-bending compared to compression, we lower the local resistance to compression of the rod. We consider this effect by setting an additional constraint on the

local stretch energy. If the length of the current edge is shorter than its values at rest ($\|e^i\| < \|\bar{e}^i\|$), we divide the local stretch energy $E_{\text{stretch}}(e^i)$ by 4.

To choose the right value for η , we want each rod segment to remain almost the same length while enabling small distortion to improve finding the optimal value. For that, we plot the maximum difference in segment length over all the time frames of the Prelude dance for different values of the stretching coefficient η in Figure 4.15. For these simulations, we set the values of the other coefficients to $\beta = 100$ and $a = 0.01$. However, we obtained similar behaviors for the difference in edge length with different coefficients for α and a . We can see that increasing the stretching coefficient in the range $[10^{-5}, 10^0]$ decreases the difference in segment rest length. However in the range $[10^0, 10^5]$, the difference remains small. However, increasing the stretching coefficient too much can increase the number of iterations of the optimization to find the optimal ribbons. It can even put the system in an unlikely optimal pose. In practice, setting $\eta = 10^1$ is a reasonable value, keeping the segment length distortion small while keeping the optimization fast and eliminating unlikely poses.

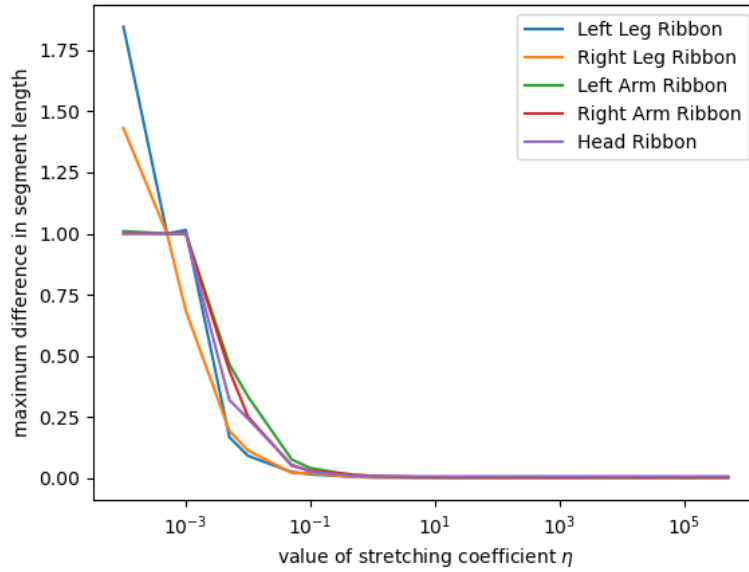


Figure 4.15 – Maximum distortion over all segment of one ribbon over all time frame with different values of the Stretching coefficient η



4.10.2 Changing the Bend Weight

The value of α defines how much the ribbons are likely to resist bending. Indeed, the higher the value of α , the more likely the optimization will favor transgressing other constraints (in this case, the closeness to the data or the stretch) than having the ribbon bend. Figure 4.16 shows the resulting ribbons with varying values of α on one pose (frame number 2416) of the Prelude dance. In practice, the choice of parameter was done on all the videos of all the recorded dances and is therefore subjective. We can see that when α is between 10^4 and 10^5 (Figure 4.16i, 4.16j), the bending weight is so high that it leads the resulting ribbons to be almost straight and not follow data. In particular, the legs do not bend at the knees when, in practice, the knees are bent. We can also observe that between 10^{-4} and 10^1 (Figure 4.16a, 4.16b, 4.16c, 4.16d, 4.16e, 4.16f) bending is more likely to happen and gives a wrinkled effect and lead to unwanted bending. We therefore chose between 10^2 and 10^3 . We can see that when $\alpha = 10^3$, the shoulders are high, and the left-hand looks not bent enough. Therefore, we set $\alpha = 10^2$.

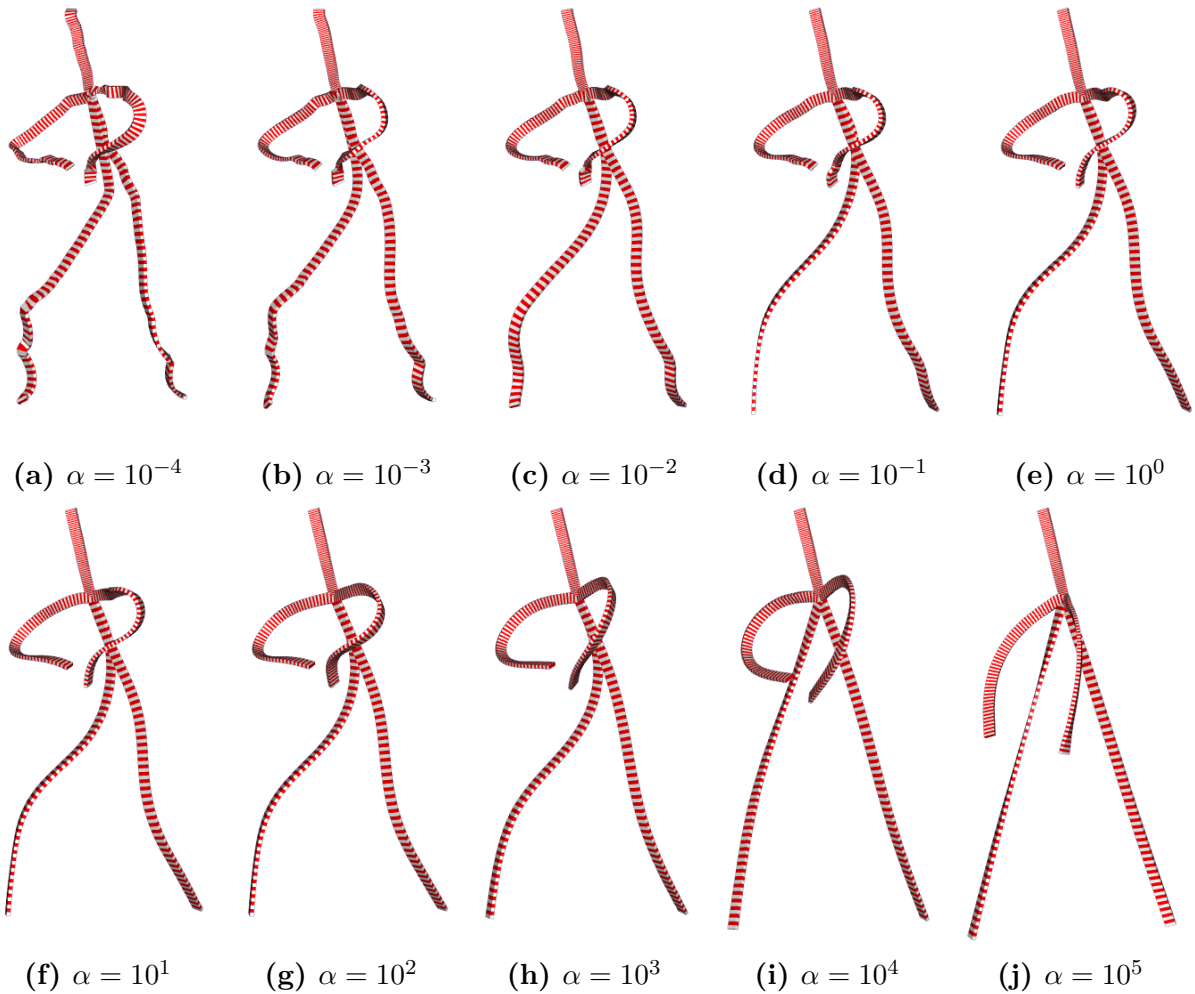


Figure 4.16 – Resulting ribbons for different values of α .

4.10.3 Changing the Linear Data Weight

The value of a defines how much the ribbons are likely to remain close to the motion capture markers. Figure 4.17 shows the resulting ribbons with varying values of a on one pose (frame number 2416) of the Prelude dance as an example. Similarly to the choice of the bending weight, the choice of the parameter was done on all the videos of all the recorded dances and is also subjective. We can see that when a is between 10^0 and 10^5 (Figure 4.17e, 4.17f, 4.17g, 4.17h, 4.17i, 4.17j) the linear data weight is so high that the optimization favors closeness to the data to low bending and stretching, resulting in wrinkled ribbon. This effect is visible especially on both arms. On the other side, when a lays between 10^{-3} and 10^{-4} (Figure 4.17a, 4.17b), the animation tends to jump from one-time frame to another temporally and we lose the fluid aspect of the animation. We therefore chose between 10^{-1} and 10^{-2} . We can see that when $a = 10^{-1}$, the left shoulder is high and over-rotated. Therefore we set $a = 10^{-2}$.

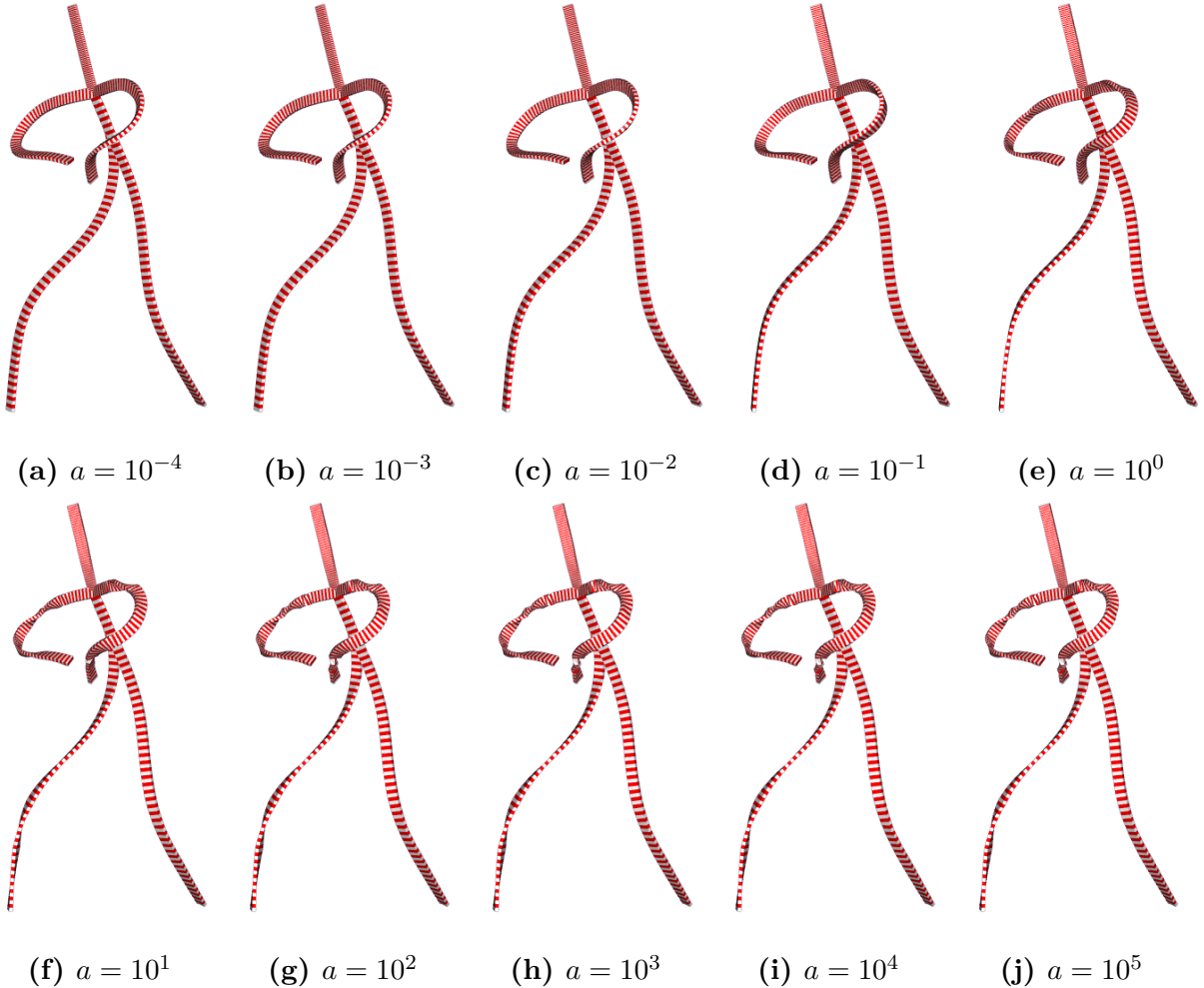


Figure 4.17 – Resulting ribbons for different values of a .



4.10.4 Changing the Twisting/Angular Data Ratio

In the case of the second optimization (finding the optimal material frames), it is enough to look at the ratio between the weight of the twist energy and the angular data energy, i.e., $\frac{\beta}{q}$ (see Appendix A.5). We fix $q = 0.1$ and make β vary to find the optimal ratio. Figure 4.18 shows the resulting ribbons for varying values of the ratio $\frac{\beta}{q}$ on one pose (frame number 2536) of the Prelude dance as an example. In practice, the choice of parameter was done on all the videos of all the recorded dances and is therefore subjective. We can see that when $\frac{\beta}{q} \in [10^{-3}, 10^0]$ (Figures 4.18a, 4.18b, 4.18c, 4.18d), the twist weight β is not strong enough compared to the linear data so that the ribbon over twists and leads to undesired wrinkled effect. We can also observe that from 10^1 to 10^6 (Figures 4.18e, 4.18f, 4.18g, 4.18h, 4.18i, 4.18j), the lower the twisting becomes, the more likely the ribbon is to twist completely, especially along the left arm. Since we want to have as much twisting information as possible without the ribbon looking wrinkled, we chose the value of the ratio as $\frac{\beta}{q} = 10^1$, which means $\beta = 1$ and $q = 0.1$.

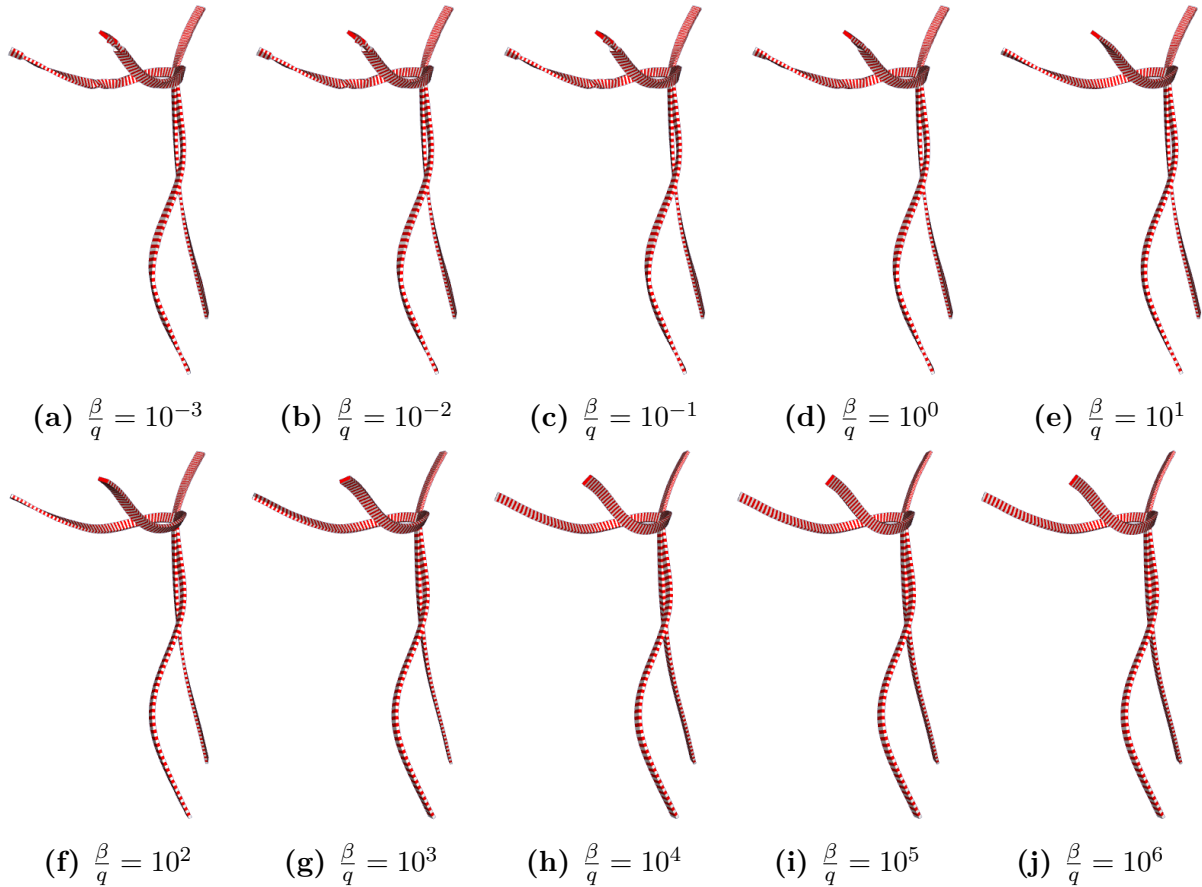


Figure 4.18 – Resulting ribbons for different values of $\frac{\beta}{q}$.

4.10.5 The Final Weights and Resulting Ribbons

The final weights that are then used to generate the ribbons are described in Table 4.1.

Energy	Stretch	Bend	Linear Data	Twist	Angular Data
Weight notation	η	α	a	β	q
Value	10	100	0.01	10	0.1

Table 4.1 – Final weights of all the energies.



Dancer's Experience with the Ribbon Model

Along with my supervisors and an intern, I conducted a series of workshops with professional dancers to articulate how they perceived and interacted with the 3D model of the ribbons. The experiments aim at assessing whether this model conveys Isadora Duncan's principles of *fluidity*, *solar plexus* and *wavelike movement* outlined during the co-design process with Elizabeth, and whether it supports the transmission of Duncan's repertoire to professional dancers.

5.1 Workshop 1

5.1.1 Designing the Set-Up

For the first workshop I decided to introduce the ribbon model in the most simple set-up possible: projected on a white screen using a projector. The idea was to put together conditions for the dancers to interact with it on screen and observe how they experience it and what it inspires them to do.

5.1.2 Participants

We invited 4 professional contemporary dancers to participate in a half a day workshop. They will be referred to as W1P1 through W1P4. All participants were woman with 20 to 40 years of experience. They had no previous experience in Isadora Duncan's dance. Elisabeth as well as my supervisor Sarah Fdili Alaoui led the study together. Sarah introduced the workshops goals and walked the participants through the interactions. Elisabeth was in charge of teaching a Duncanian Dance to the participants. I was in charge of setting up the model and gathering data (video, audio, handwritten notes etc.).



5.1.3 Procedure

The workshop took place in a local dance studio, which had chairs and a table. Elisabeth first led everyone (all participants and researchers) through 1h30 warm up that prepared them to dance Duncan's repertoire. Subsequently, she taught all participants and researchers the "Moment Musical" dance of Isadora Duncan without technology for approximately 1 hour.

We then asked the dancers to observe the final starfish ribbon model performing "Moment Musical" projected on a white screen using a projector. The video was mirrored so that it was easier for the dancers to follow the models' movements. We asked them to dance with the model all together in one group. We had the dance shown to them as long as they wished. They danced with the video for approximately 30 minutes.

After this experience we sat all together on the floor, and run a conversation with all the participants on their experience of the model as shown in Figure 5.1.



Figure 5.1 – Dancers discussing their experience.

5.1.4 Data Collection

I placed a camera on a tripod in a corner of the studio to record video and audio of the session. I also set an audio recorder during the group discussion to record audio of what the participant told us. We took pictures at various moments of the workshop. I also took personal notes on what we observed during the workshop.

5.1.5 Data Analysis

My supervisor Sarah Fdili Alaoui and I analysed the data. We revisited all of the audio-visual material and took notes of significant events in the videos. We also transcribed the audio material. We analysed all of the transcriptions using a thematic analysis approach (Guest et al. 2012). First, we defined concepts using our original words (open coding) and grouped them in themes (axial coding) that are represented in each subsection of the findings. Our themes represent common patterns across participants that capture their perception and experience of the model and identify opportunities and limitations that might trigger new design and experimental ideas.

5.1.6 Findings

5.1.6.1 Dancing with an Abstract Body

Dancers were inspired by the fact that the star-like model did not refer too closely to a human: *“And it’s crazy how we can reconstruct from something so minimalist and rudimentary and how it could capture the ‘essence’ of the movement”* (W1P1). This made them focus on “the essence” of the movement and the lines of the body: *“It is the body reduced to its elementary lines”* (W1P2).

One participant emphasized how the model could be perceived as a representation without gender nor cultural references to it which allows to focus on the movement rather than its context. *“And what I find funny is that the character which does not have any muscle nor bone, we don’t know who he is, since it is so abstract, that with respect to the dance, I find it really interesting, it would enable a non connoted knowledge. It is interesting this lack of connotation. No gender, no cultural connotation. To which time frame does it belong. If I propose this to a student-dancer right now, who would not know who Duncan is, I would like to know what they would say”* (W1P3).

Another participant found that an abstract representation brought forward the poetry that is inherent to movement besides the costumes and the historic context of the dance: *“I found it poetic, even if we removed the costumes, the dancer’s body, all of the imaginary world of Isadora Duncan, and everything that she put behind her philosophy of dance. Even if we remove all of it, this character and the music there is already a lot poetry that comes out”* (W1P4).

5.1.6.2 Dancing with a Natural Body

Fluidity of the movement is also a main quality that the dancers could see in the ribbons' movement: "*We really see the liquid, the fluidity, we really see it a lot. There is a big fluidity of the spine, an opening of the spine. There is a continuum*" (W1P2). Because the ribbons were so simple yet their motion was implemented to account for the wave-like fluid quality of movement in Duncan's repertoire, dancers were able to distinguish such quality in the movement of the model accurately. One dancer said : "*We can really recognize something that can connect to the intention of the body which is clear. We can see that it is Elisabeth that is dancing. That there is something regarding the intention of the movement, without the hand, without the eyes, in the fluidity, the musicality*" (W1P4).

Additionally, dancers considered that the star-like representation visualized how the movement was initiated from the solar plexus: "*We can see movements starting from the plexus*" (W1P2).

5.1.6.3 Dancing with a Flat Screen

Although the dancers appreciated and recognized the movement qualities of Duncan in the simple yet expressive motion of the ribbon model, they reported on the difficulty to look at it on a flat screen. And more so, the dancers found it difficult to look at it while dancing. One participant said: "*When we turn around we don't see the screen*" (W1P3). Another dancer (W1P4) reported that they were more likely to look at other dancers around them before looking at the screen and that it was their last resort to understand the choreography. Additionally, the dancers expressed that such a visualization of the model lacked information on depth, and that therefore it was difficult for them to follow the model while dancing. They suggested the possibility to slow down the model to decipher more information on the dance.

This showed how a 2D representation through video was limited and did not convey enough information from the 3D model for dancers to learn and experience from.

5.2 Workshop 2

5.2.1 Designing the Set-Up

For the second workshop I decided to move away from the projection on screen and experiment with virtual reality. We explored the HTC Vive 2 headset. However that set-up

constrained the space to 3 by 3 square meter. Moreover, the headset was too heavy and balanced enough (more weight is put on the front of the head compared to the back), and the cables and space limitations restrained the movement. Additionally, handling the controllers was cumbersome, and retained dancers even more from dancing freely with the set up. Following these explorations, we decided to experiment with a Hololens 2 which is a wireless mixed reality headset. This device allowed us to display our model in 3D. Moreover, the Hololens 2 headset is wireless and does not require controllers because it can track hand movements. Therefore, the dancers can use their hands to select options and dance. Finally, it does not require a constrained space, and the dancers can share the same space as the animation. In (Raheb et al. 2019), it is argued that having a portable device that can be brought into a dance studio, where dancers are used to perform their art is the best option, and therefore argue that using a Hololens 2 headset is a great option for dance learning.



Figure 5.2 – Different poses of the ribbon model as seen through Hololens.

To put our ribbon model into the Hololens 2 headset, I first converted the resulting animation from chapter 4 (one mesh per frame) into Blender using blendshapes. I then created one blendshape per frame and baked the animation and exported it in the FBX file format. Finally, i imported the FBX file in the Hololens headset using Unity. Figure 5.2 shows how the ribbon model is displayed inside the headset.

With the help of a research engineer, I implemented different features in an interface in the Hololens 2 headset, following some of the dancers suggestions. One feature allows the dancers to start and stop the animation whenever they want. A second feature enabled them to slow down and speed up the animation. All these features were accessible to the dancers in the main menu which they could access by raising their left hand in front of them and selecting the desired feature by clicking with their right hand, as shown in Figure 5.3.



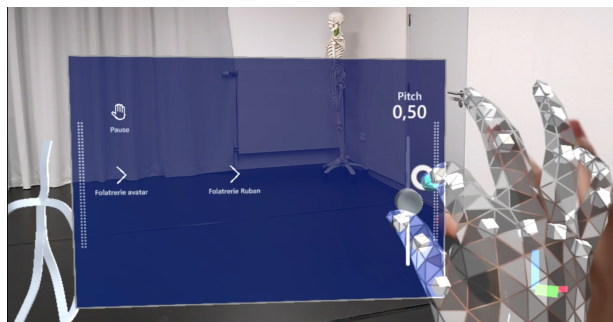


Figure 5.3 – User Interface in the Hololens 2 headset.

5.2.2 Participants

Along with my supervisors, we invited 5 professional contemporary dancers to take part into the second workshop. We will refer to them as W2P1 through W2P5. All of them were woman with 20 to 40 years of dance experience. 3 participants out of the 5 took part in the first workshop (W1P1, W1P2 and W1P3). They kept the same participant number as the first workshop. They had no previous experience in Isadora Duncan dance, except what they learnt in the first workshop.

Elisabeth as well my supervisor Sarah Fdili Alaoui led the study together in the same fashion as in the first workshop. I set up the model and the Hololens experience and gathered data.

5.2.3 Procedure

The workshop took place in the same local dance studio. Elisabeth first led all participants and researchers through a 1h30 warm up that prepared them to dance Duncan's repertoire. Subsequently, all participants and researchers were taught for 1h30 the "Folatrerie " dance of Isadora Duncan by Elisabeth without technology. Then we had the dancers visualize the ribbon model performing "Folatrerie" in the Hololens headset.

Elisabeth and the 5 participants were introduced to the Hololens experience. Subsequently, each one had 10 minutes to experiment with the model in the headset individually. I suggested them to visualize the dance as many times as they wanted. During the time with the headset, they were able to freely move in the dance studio as shown in Figure 5.5.

After this experience we sat all together (Elisabeth, me, Sarah, as well as all participants) on the floor, and ran a conversation with all the participants on their experience of the model.



Figure 5.4 – Two dancers using Hololens menu at the same time.

5.2.4 Data Collection and Analysis

Data collection and analysis was performed in the same way as in Workshop 1.



Figure 5.5 – One dancer dancing with the Hololens headset on.

5.2.5 Findings

All participants thought that the ribbon viewed in augmented reality was visually appealing and allowed them to appreciate and “contemplate” the choreography. Dancers particularly appreciated how the model helped them learn the choreography. Overall they reported on how the model was suitable to convey the movement qualities of Isadora Duncan.



5.2.5.1 How the Star-Shaped Body Represents a Duncanian Body

The dancers appreciated this visualisation of the body and considered it representative of Duncan's quality of fluidity. Because the model used in the second workshop is the same as the one used in the first workshop, we received very similar feedback on the perception of the inherent movement qualities of the ribbons, which were seen to accurately display the qualities of the natural movement of Isadora Duncan. One participant said *"It is a perception that I really like. It lets me see lines, moving curved lines in a form of fluidity which lets us see how the movement circulates"* (W2P2).

They discussed different possible representations, including one with one line for the arms, one line for the legs and one line for the spine and a circle for the head as shown in Figure 5.6, but thought the one we chose fits the aesthetics of Duncan's choreography. *"I don't know if this model (see Figure 5.6) is suitable"* said one participant (W2P5). To which Elisabeth responded *"Yes I prefer the model that we saw. I think there has been a choice that corresponds to an aesthetic. And I think it is important to make a choice. If this was Martha Graham maybe the choice would be different. But for Duncan it needs to fit the aesthetic of the body"*.

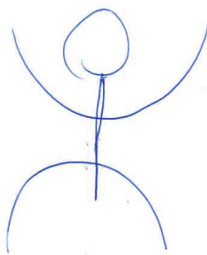


Figure 5.6 – Doodle of another possible representation of the dancer's body proposed by workshop participants.

5.2.5.2 Hands, Feet and Head

Four dancers did not notice or were not bothered by the lack of fingers, correct feet representation and lack of a round head. However, the lack of feet was interpreted as a lack of anchoring to the ground: *"Maybe it would be good to see the ribbon anchoring itself to the ground"* (W2P3).

In fact the idea of anchoring to the ground was central in the participants answers and was somehow controversial. Some found that the lack of feet did not carry the information on the relationship to the ground, and others thought that it showed it even better. One participant thought that the lack of feet was keeping her from understanding the relationship to the ground: *“it seems to be floating and we don’t understand because the choreography demands a lot of grounding”* (W2P1). The floating feeling was however perceived by another dancer as showing the wave propagation of the movement (W2P5). Elisabeth considered that the lack of explicit reference to the feet showed the relationship to the ground even more: *“And it’s funny paradoxically we can feel the ground better almost”* (Elisabeth). One participant noted that *“we see the ribbon deforming from the feet to the hips, we feel the resilience, we feel the relationship to the ground, and then how the wave propagates in the body. And the ribbon lets us see all that”* (W2P4). Another participant stated that *“There is maybe less of a relationship to the support of the feet where you see more weight. But here we are less focused on support, but more on moving lines, and how energy circulates in a curved way, there are really few straight lines”* (W2P2).

5.2.5.3 Fluidity and Ripple

All dancers agreed that the ribbon model displays the fluidity of the movement. *“Yes the ribbon gave visibility to the fluidity of the speed of the spine and the arms”* said (W2P5). Another participant said: *“With the ribbon I saw the small loops described by Duncan’s expert, the small fluidity”* (W2P1). A quality of movement that the participants also linked to the fluidity is the ripple of the body, meaning the way the movement circulates through each body part. The participants also thought that the ribbon model is relevant to transmit such a quality of movement: *“[Talking about why they like the ribbon] I think it’s the elasticity, we really see the ripple”* (W2P5). Another participant said: *“I took note of nuance of articulations but it’s also the ripple effect, circulation of the movement between the top and bottom of the body”* (W2P4).

5.2.5.4 On Abstract Visualization

All the dancers reported on how the model was particularly suitable for a dance like Isadora Duncan’s where the focus is not on the body per se, or specific postures or movements to perform, but rather on the movement qualities themselves. The abstraction of the ribbon allowed them to observe and embody such qualities instead of focusing on the form of the body. The dancers reported on how the ribbon better conveyed the properties of fluidity and undulation than a “normal avatar”: *“I have appreciated the choreography with the ribbon, maybe because the image of the ribbon is more poetic than an avatar, more aesthetic*



and because we can better see and with more precision the fluidity of the movements and motions” (W2P3).

They mentioned that the ribbon was smooth and nice and “not aggressive” which invited to dance with it even more: *“Spontaneously I find it really nice to see. It is really smooth and not aggressive. [...] The ribbon seduced me a lot” (W2P2).*

5.2.5.5 On the Use of Augmented Reality

While in the first workshop we could observe how the dancers were not able to follow the ribbon on screen, when using augmented reality, we saw them follow it, replay it multiple times and play with its speed to learn different aspects of the dance from the model.

The device itself presented multiple challenges to the dancers as many had difficulties using the menu with air gestures. Additionally dancing with a headset was a completely new experience to them. *“There is still an adaptation time, to understand how it works” (W2P3).* Moreover, having a 3D animation moving in the same space as them lead the dancers feeling lost in space *“The ribbons keep on changing direction which confused me on the choreography that I had learned in real life. I lost the notion of space.” (W2P6).*

Because of the challenges and novelty of such a set-up, some dancers first observed the dance in the headset. They then marked the movement slowly with their body while following the ribbon in slow motion (they used the slow down feature in the interface to do so). Marking a movement in dance means executing it in a simplified, schematic or abstracted form. The dancers then progressively started performing it following the ribbon with the normal speed. One participant said: *“There is first a time of observation, then a rapid need to enter the dance” (W2P2).*

They reported on the need to get used to the technology in order to fully appreciate the dance: *“My visual perception wasn't trained for that but I like to discover and acquire new skills”* said another participant (W2P4).

Despite the limitations of displaying the model on Hololens, we could still observe how the dancers explored the features of the interface (mostly slowing down and stopping the ribbon) and embodied the dance with the ribbon. With the headset on their head, they performed the dance using a large part of the space of the studio and paying attention to the qualities of fluidity, the wave and the initiation from the solar plexus.

5.3 Discussion

5.3.1 What Have Become of Our Design Principles?

The three main Duncanian principles that we outlined from our discussions with Elisabeth were the fluidity of the movement, the solar plexus as a center of energy and the wave-like propagation of the movement. The co-design consisted in multiple conversations with Elisabeth as an expert in Duncan's style in order for her to assess how the prototypes that we produced embodied fluidity and wave-like movement that initiated from a place that could be perceived as a solar plexus. In the workshops where professional dancers experimented with the graphical models, we found that they strongly perceived the ripple starting from a center that was seen as a solar plexus and circulating towards the extremities of the star like ribbons. Moreover, they expressed how the ribbons embodied qualities of fluidity, naturalness, undulation, propagation, elasticity and continuous movement that are central to Isadora Duncan's repertoire. These rich perceptions of the ribbon supported their embodiment of the Duncanian dances. Our model was seen as an expressive re-enactment of Duncan's dance that made them reflect on the specifics of this vocabulary either by praising its qualitative capacities or by critiquing how it ignored an important aspect such as "ground support through the feet on the floor". Moreover, they saw its abstraction as 'interesting' and allowing to focus on the "essence" of the Duncanian movement rather than the form of the body, which is irrelevant in Duncan's repertoire. The richness in the perceptions of the movement were possible because of the elaborate physical model that we computed. This echoes (Fdili Alaoui et al. 2015) that showed the potential of physical models to express movement qualities in dance. It was also possible because of the methodology that we used centred on the connoisseurship of Elisabeth Schwartz and where we explicitly iterated on our choices according to her feedback which helped us to design a model that conveys faithfully Duncan's movement qualities.

5.3.2 Simple Interactions and Complex Perceptions

Our system (the ribbon model viewed in augmented reality) provided simple interactions such as slowing down or accelerating the model. Through these interactions, the dancers were able to play with the system in order to observe the ribbon in the speed that they wanted. They started by slowing the ribbon down and observing it while marking the movement. As shown by Kirsh (Kirsh 2013), marking movement in dance (to execute a dance phrase in a simplified, schematic or abstracted form) allows dancers to think with their body and facilitates their real-time reflection on the dance. We were able to observe how the dancers used the system to mark the dance phrase prior to performing it fully



which supported how they embodied and memorized it. The dancers also moved in space with the Hololens headsets to observe the ribbon from the perspectives that they wanted. This allowed them to adjust the conditions to follow the ribbon and observe details that were not accessible to them. Nevertheless, our results illustrated the tensions that come from using a device such as Hololens in a context such as dance. Indeed the headset provided an opportunity to see the dance in a novel and insightful way through the visual ribbon displayed. However, it also limited the embodied experience of the dancers, as they had to move carefully within the space allowed by the interaction and at times shift their focus outwards to perform the mid-air gestures that control the menu.

5.3.3 Valuing Embodied Knowledge Above All

We described the co-design process of an abstract visualization of dance movement qualities based on the collaboration with a connoisseur dancer of Isadora Duncan’s repertoire. We value in this work the extensive and precious input from Elisabeth. More than simple input, Elisabeth was one of the initiators of the project and co-author of the paper that was published as a result of this research (Vialle et al. 2022). She was curious of how technology could carry information on dance and how computer graphics have the capabilities to represent the qualities of Isadora Duncan. Her knowledge of the dance, both theoretical and embodied, was built over 40 years of learning this repertoire and transmitting it to other dance artists. She dedicated all her career to building an intimate understanding of Isadora Duncan’s repertoire. She used her knowledge in accompanying every step of the project, from infusing ideas on possible designs, to giving feedback on the models, to demonstrating the movement when necessary to translate its qualities to my research team. We believe that such collaboration putting at the center the expertise of a connoisseur is fundamental in the design of technologies to support dance and kinesthetic creativity. Moreover, we value approaches of dance that dig into specific vocabularies in a deep and committed way, avoiding the universality of generic and all-encompassing dance languages. The diversity of styles and choreographic approaches in dance is an endless source of embodied knowledge that HCI researchers have started digging into (Ciolfi Felice et al. 2018).

This work does not seek to provide standard generalizable and universal models of dance movement. Instead it contributes with a model specifically tailored for the work that we spent a long time learning and dissecting.

5.3.4 Transmitting a Vocabulary to Safeguard a Human Heritage

These experimentations allowed both the researchers and the dancers to deepen their knowledge of a dance style that is in danger of extinction. Indeed, the experimentations

were situations of building and circulating an embodied knowledge about Isadora Duncan's work. In the co-design process, we cared that both researchers and dancers engaged physically with the material and performed the pieces with their own body to better articulate what the Duncanian style meant for them. The researchers used that knowledge to reflect on the ribbons' design. The dancers used that knowledge to enrich their palette of embodied capabilities with a dance style that they had no previous opportunities to learn nor to perform. Thus, we consider our experimentations as attempts to make Isadora Duncan's heritage alive again, in the studio. The transmission sessions with Elisabeth, mediated by technology gave the dancers an embodied experience of an archive that so far is stored only in the embodied memory of the expert Duncanian dancers that remain. Therefore, a contribution could also be seen as building a living archive of a repertoire that was almost dead but that is fundamental to what has become today's modern and contemporary dance, with its freedom and poetry.



Part II

How can the Perception of Space be Enhanced in Dance Using Augmented Reality?



Résumés en français des chapitres

Chapitre 6

Dans ce chapitre, nous exposons la suite de notre processus de co-conception avec notre danseuse experte, dans le but cette fois-ci d'améliorer la perception de l'espace pour les danseurs. Nous nous sommes inspirés de la notation Sutton, une notation de la danse représentant le corps comme un ensemble de traits représentant les membres ainsi que le tronc et la tête. Notre co-conception s'est également déroulée sous forme d'itérations avec notre experte danseuse sur nos différents prototypes. Le prototype final montre nos rubans animés, ainsi que la trace laissée par le plexus solaire dans l'espace et ce que nous appelons des moments d'impulsion, de petites animations des moments clés de la chorégraphie.

Chapitre 7

Dans ce chapitre, nous exposons comment nous avons évalué notre système en utilisant une méthodologie d'observation structurée afin de déterminer combien de moments d'impulsion il est préférable d'afficher simultanément. Cette évaluation a eu lieu sous la forme d'un atelier d'une demi-journée avec des danseurs. Nous avons intégré nos différents prototypes (montrant différents nombres de moments d'impulsions simultanément) dans un casque de réalité augmentée. Nos résultats montrent qu'il n'y a pas un prototype qui est meilleur que les autres, mais plutôt que chaque prototype apporte des solutions différentes en fonction des besoins des utilisateurs. Nos résultats montrent également le potentiel de la réalité augmentée dans le cadre de l'apprentissage du mouvement dansé.



Supporting Perception of Spatiality in Dance in Augmented Reality

6.1 Building a New System

To improve the system presented in Chapter 3, 4 and 5 we continued the co-design process with Elisabeth. We decided to focus on one of the main drawback that the dancers experienced in the Hololens 2 headset with the ribbon model: dancers were getting lost in space which confused them about the choreography “*The ribbons keep on changing direction which confused me on the choreography that I had learned in real life. I lost the notion of space.*” (W2P6). This part of the co-design process took place during the second half of my PhD. The co-design process consisted of various meetings and conversations that took place in person, in Elisabeth’s apartment, or through calls and e-mails. It also consisted of my supervisor Sarah Fdili Alaoui and I taking classes with Elisabeth regularly over a six month period. During the classes, Elisabeth taught pieces of Duncan’s repertoire and transmitted the history and philosophy behind Isadora Duncan’s work. These classes and conversations were a way for the authors to understand Isadora Duncan’s qualities of movement in an embodied way and to use that knowledge directly in the design of the system. Throughout the design process of the system, we showed videos of the prototypes to Elisabeth and had discussions with her through video calls (see Figure 6.1) and in-person meetings.

6.1.1 Inspiration from Sutton Dance Notation

We took inspiration from the Sutton dance notation to create our prototypes. In the Sutton dance notation, the human body is simplified into stick figures. The notation represents the dance through a written score showing the displacement of the stick figures in space. Figure 6.2 shows the Sutton notation of the Prélude dance.

It was natural to use the the ribbon models that we have developped during the first part of the PhD. Figure 6.3 shows an early comparaison between the ribbon model and the



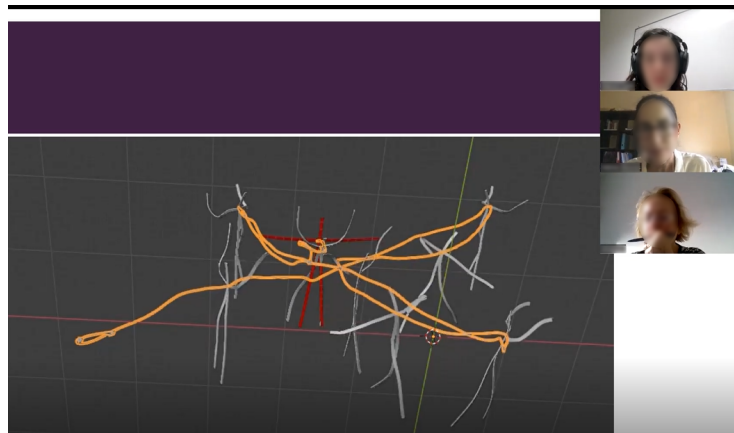


Figure 6.1 – Zoom meeting with Elisabeth to discuss the second prototype.

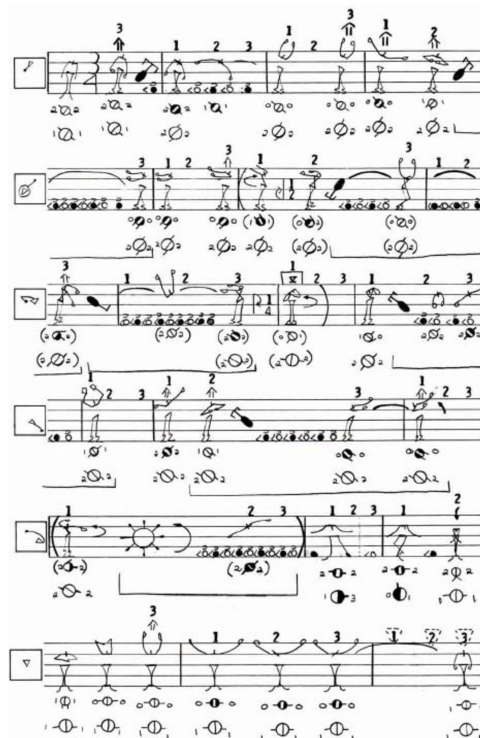


Figure 6.2 – Sutton notation of the Prélude dance choreographed by Isadora Duncan (image source: www.dancewriting.org, CC BY-SA 3.0).

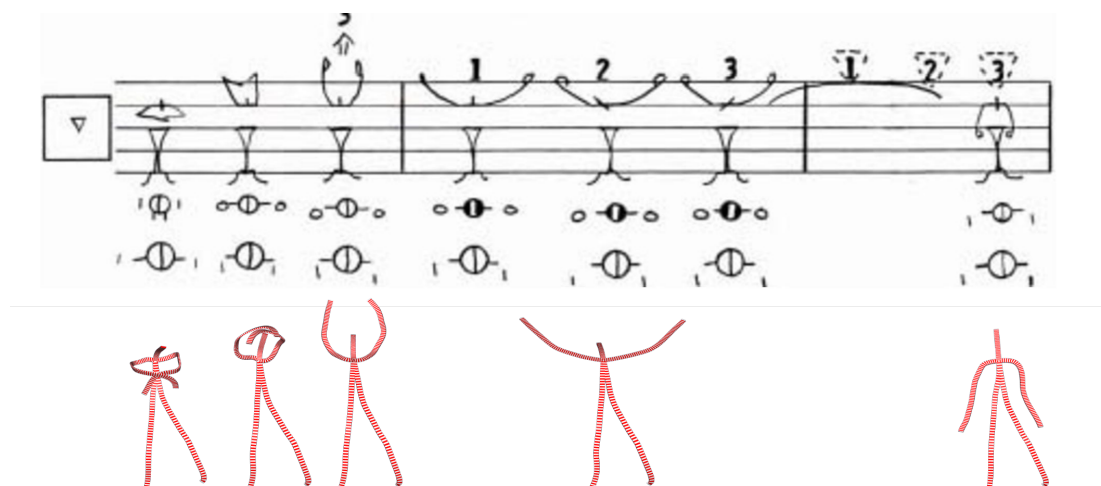


Figure 6.3 – First idea of comparing the ribbon model and the Sutton notation

stick figure used in the Sutton dance notation. To render the dance's spatiality, we wanted to design a system that visualizes the trace of the body's position in space. Since we are working on the ribbon model (Vialle et al. 2022) that is centered around the solar plexus, our first idea was to display the trace that the solar plexus leaves in space. This would emphasize the centrality of the solar plexus. Moreover, the trace displayed in time would help dancers understand the temporality of movement and its spatiality, which was lacking in the first design.

In dance, notation consists of translating something continuous (dance) into something discrete (a finite number of symbols written onto paper). Inspired by Sutton's notation, we decided to use key poses, also known as keyframes in computer graphics, which would be placed along the line of the solar plexus. These keyframes would visualize key moments of the choreography placed in a 3D space. While discretizing the choreography seems to contradict Isadora Duncan's philosophy of continuous and fluid movement, it corresponds to how Elisabeth teaches it. Because it is difficult to learn the choreography from start to finish all at once, Elisabeth segments it into "sequences" that she demonstrates one after the other. In our system, the discrete keyframes serve as visual and spatial prompts that indicate the main movement in each sequence that forms the choreography.

A question that emerged is how to choose which keyframe is important to be displayed. In other words, how to determine which moment of the dance is important to be shown?

According to the connoisseur, key moments in the choreography relate to when the dance is quick or sustained or when it is changing orientation. We used the ribbon model's energy as a reference to identify those moments. We interpreted the moments where the energy was the highest to be the moments with the most interest. The idea was to display those



key moments as stick figures shown in 3D space and connected through the trace of the solar plexus.

Along with the connoisseur, we wanted a visualization that would help dancers to engage with the dance in an embodied way. We decided to add a red ribbon that would "perform" the dance along the line of the solar plexus and go through each keyframe when it is performing that specific movement. Having a red ribbon would serve as a guide for users to be able to follow the dance. The keyframes displayed in white would help users know what will happen next in the dance. They would provide a *feedforward* that gives information to the dancers on the key future moments of the dance that the red ribbon would be performing.

We also discussed with Elisabeth the choice of the dance to work on. We decided to work on the Prélude dance because its displacement in space is central to the dance. Elisabeth said "*Yes, here it is really good because we really see the construction in space, for prelude it is in a star shape. It is clear in the four diagonals.*" As shown in Figure 6.4, the spatiality of the trajectory forms a cross-like pattern that can be visualized easily.

6.1.2 First Iteration of the Design

Following these first design choices, I developed a first prototype. We shared it with Elisabeth on video and discussed with her experience of the system.

She pointed out that having static poses was counterintuitive to the idea of continuous movement in Duncan's style: "*When it comes to Duncan, as you may have understood, the question of sequencing is complex because she doesn't conceive movement by sequence or cutting unlike other choreographers.*"(Elisabeth). Indeed in Duncan's philosophy of movement, the movement is always in a continuous curve. It is propagated in a wave-like motion. Impulse in movement is what makes a wave continue expanding and retreating, and so on. To address this issue, we decided to display small animations for a few seconds instead of static poses. These animations correspond to the impulse moments that "pick up the dance as it continues" (Elisabeth). For the dancers to perceive these animated impulse keyframes throughout the dance, we decided to loop them. In the rest of the paper, we will call these small animations *moments of impulse*.

6.1.3 Second Iteration of the Prototypes

The resulting prototype of this iteration is shown in Figure 6.4. After sharing it with Elisabeth, we discussed with her what could be improved in the new prototype.

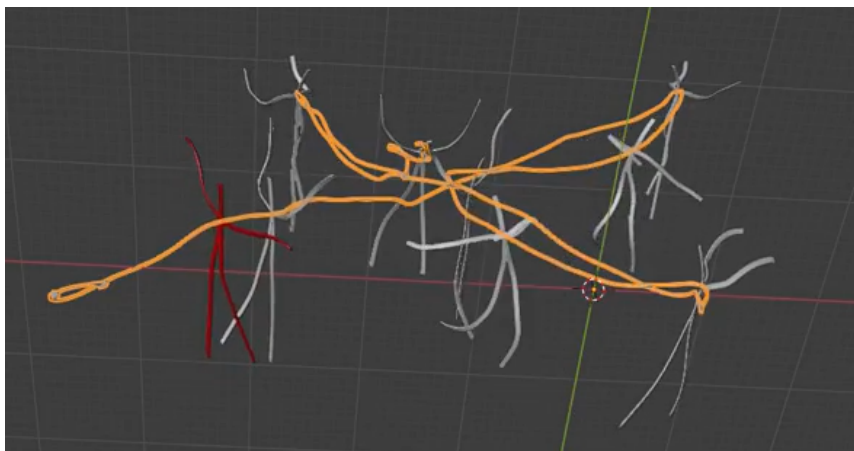


Figure 6.4 – The first prototype displaying the keyframes in white, the line of the solar plexus, and the red ribbon that "performs" the dance.

We discussed with Elisabeth how many moments of impulse are needed to be displayed at the same time. One thing that stuck out was that the moments of impulse needed to disappear when the red ribbon entered them because afterward, they were not relevant to the rest of the choreography. Moreover, displaying past moments of impulse would make the space crowded, making the rest of the dance hard to decipher.

This also led us to question whether it was necessary to show all the moments of impulse or a limited number of them since we cannot focus on all of them at the same time. Therefore, we decided to develop two new versions of the prototype. One version would display solely one future moment of impulse, and another version would display all the future moments of impulse.

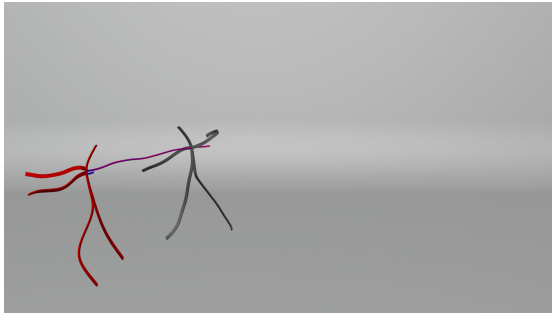
We shared those two versions with Elisabeth. Seeing them led her to question the visibility of the line of the solar plexus. We decided to try two versions: the first one would display the entire line of the solar plexus, and the second one would display only the part of the line leading to the next moment of impulse.

To enhance visibility, we also added color to the line of the solar plexus. The color corresponds to the speed at that particular instant: the slowest the movement, the closer the color to blue, and the fastest the movement, the redder the line.

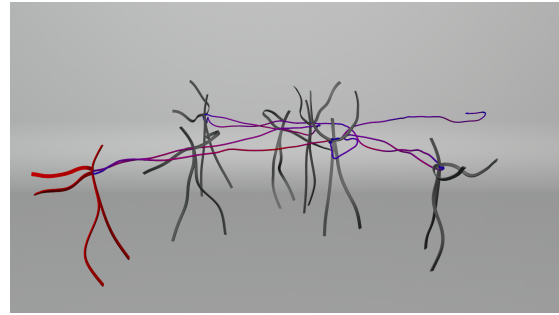
6.1.4 The Final Prototypes

We showed Elisabeth the prototypes and discussed them with her. We discovered that the color of the solar plexus line was irrelevant to her, as it was not obvious to her that it





(a) The first version displays only the next moment of impulse, the red ribbon, and the colored plexus line connecting the previous moment of impulse and the next moment of impulse.



(b) The second version displays all the future moments of impulse, the red ribbon, and the entire colored plexus line from start to finish.

Figure 6.5 – The two prototypes created after the second iteration on the system

mapped to speed. She also thought that not displaying information about the speed was a good way of giving freedom to users to appropriate the choreography's dynamics and make them their own.

In addition to that, Elisabeth thought that the loop animations were “too harsh” and that we needed to add a pause after each animation to make the looping appear more smooth. This would be more coherent with Duncan's qualities and general style that favor smooth and continuous movements. Through testing with Elisabeth, we decided on a duration of 0.8 seconds for each moment of impulse.

We felt like the number of visible moments of impulse was a critical parameter of the system that we were creating. Therefore we decided to create a third prototype that would be a compromise between the two previous prototypes. It would display the next three visible moments of impulse. In the following, we will call the first prototype that displays all the moments of impulse “*Prototype all keyframes*”. We will call the second prototype that visualizes solely the future moment of impulse “*Prototype next keyframe*”. We will call the third prototype that visualizes the three future moments of impulse “*Prototype three keyframes*”.

When testing the system, we observed that because the red ribbon was performing the dance, it led us to simply watch rather than engage with it. We wanted to see if removing the red ribbon could help dancers engage physically with the prototype by following the feedforward and dancing toward the future moments of impulse with their bodies. After a few tests with Elisabeth, we realized that when we removed the red ribbon, she lacked information about where she was at in the choreography. It did not achieve the original goal of engaging the dancers more with the prototypes. Instead, it led to more confusion.

To fix this issue, we decided to have the trace of the solar plexus disappear as the red ribbon would have entered into the moment of impulse. This way, the dancers could still see the red ribbon in space while having the solar plexus trace disappear to indicate where they could follow the model and dance with it. An overview of the features of each prototype is summarized in Table 6.1.

Building on the previous models, we continued to use the Hololens 2 headset to display the prototypes. Figure 6.6 shows a view of each prototype seen through the Hololens 2 headset.

Following the design process, we became interested to see how the number of moments of impulse impacted the dancers' understanding and perception of Duncan's choreography in space.

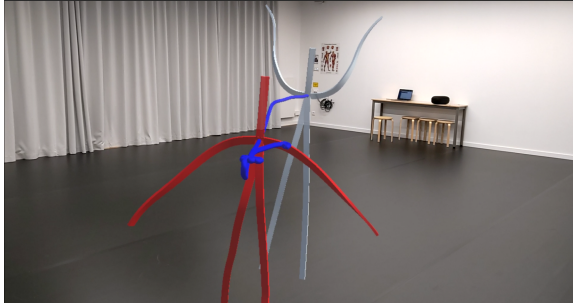
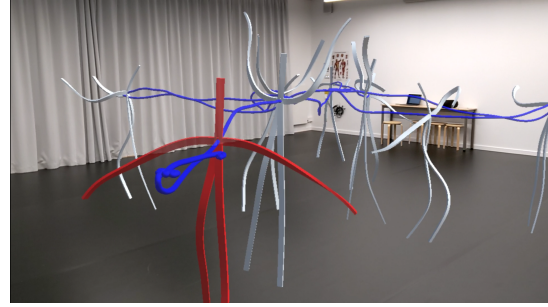
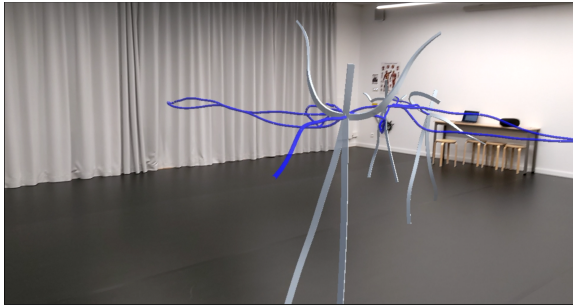
	<i>Prototype next keyframe</i>	<i>Prototype all keyframes</i>	<i>Prototype three keyframes</i>
Number of visible moment of impulse	Next	All	Three next
Visibility of the trajectory of the solar plexus (blue line)	Just the line between current and next moment of impulse	All of it	All of it and it disappears as the red ribbon animation would have entered it
Red ribbon presence	Yes	Yes	No

Table 6.1 – Features of each prototype.

6.2 Implementation

To animate the ribbon model, we followed the implementation described in Chapter 6. Then we created a new keyframe extraction algorithm (described in Section 6.2.1.2) to select which keyframes will be displayed in the prototype. Lastly, we created the augmented reality setup as described in Section 6.2.2.



(a) *Prototype next keyframe*(b) *Prototype all keyframes*(c) *Prototype three keyframes***Figure 6.6** – View of each prototype in the Hololens 2 headset.

6.2.1 Keyframe Extraction

Keyframe extraction from motion captured data is widely used in computer graphics in order to compress data. Indeed instead of having to store one pose per frame, animators store a certain amount of keyframes, and in between the keyframes the current pose is interpolated (usually cubic interpolation between the quaternions at each joint) and therefore doesn't need to be stored. This significantly reduces the number of keyframes. Keyframes are therefore chosen so that they produce the most realistic interpolated motion possible.

6.2.1.1 Previous work

When automatically extracting keyframes, there are several methods that can be used and can be grouped into 4 categories : clustering (Rallis et al. 2017), (Halit et al. 2011), optimisation based (Huang et al. 2005; Rallis et al. 2018a), curve simplification (Lim et al. 2001) and more recently machine learning methods (Protopapadakis et al. 2020; Mo et al. 2021). Clustering consists of creating clusters of poses that are alike and choosing one representing pose per cluster. Optimisation based algorithm look at minimizing an energy function that reflects how good the keyframes are according to a set of constraints. Curve simplification looks at the motion capture data as curve in a high dimensional space and

Keyframe selected by Elisabeth	554	698	755	847	904	1043	1151	1499	-
Keyframe selected by our algorithm	153	642	745	847	935	1124	1248	1456	1876

Table 6.2 – Keyframe numbers

using curve simplification algorithms to reducing it to a set of points. Lastly, machine learning algorithms are trained on already existing sets of keyframe and motion captured data and learn how to chose new keyframes in new motion captured data. For most of the methods, evaluation is performed as calculating the frame by frame difference between the interpolated animation and the original motion captured animation.

In our particular case, we want the algorithm to yield keyframes that help the dancers the most, and the human eye does not interpolate keyframes mathematically. Therefore a few methods were introduced specifically for dance summarization (Voulodimos et al. 2018; Rallis et al. 2018b). Both papers focused specifically on Greek folk dances.

They evaluate their system by evaluating the distance between the resulting keyframes and ground truth keyframes, which were selected by experts dancers. However, this does not take into account the time component of the dance. Moreover, following our co-design process, we want an algorithm that is good at retrieving keyframes specifically for Isadora Duncan’s dances and not for Greek folk dances. We therefore create a new algorithm that is tailored to Isadora Duncan’s style.

6.2.1.2 The Algorithm

We extracted the keyframes based on the moments of maximum impulse. To do so, we looked at the bending energy curve of the ribbon model with respect to time (see Figure 6.7). We then used a peak extraction algorithm (Scipy’s (Virtanen et al. 2020) *find_peaks* algorithm (Du et al. 2006)) on the curve to get the moment where each impulse was located. This gave us the specific time when our moments of impulse were located. We compared them with keyframes selected with Elisabeth. Figure 6.8a shows the resulting keyframes and Figure 6.8b the keyframes selected by Elisabeth, and Table 6.2 show the corresponding keyframe number. We can see that while some keyframe selected by the algorithms are almost the same as the ones selected by Elisabeth, there are still some inconsistencies. We decided to stick with Elisabeth’s selected keyframes, as they are more accurate to Isadora Duncan’s movement. However in future work the algorithm could be improved by taking into account the “U-turns” in the space trajectory of the dancer. This could be achieved by taking into account the curve left by the solar plexus in the 3D space and running a new peak extraction algorithm on the resulting 4D¹ parametrized curve.

¹the position of the plexus is 3-dimensional, and the bending energy adds another dimension



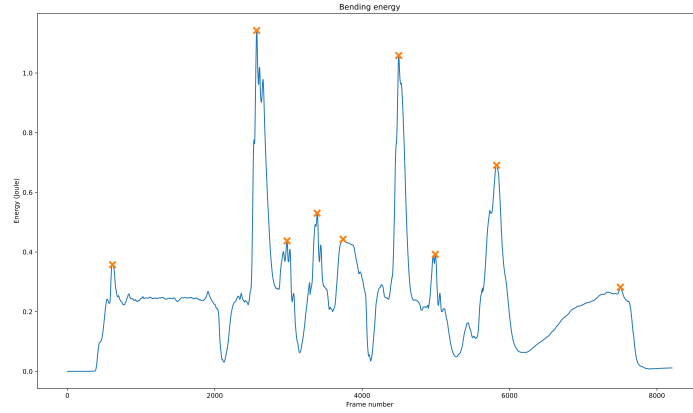
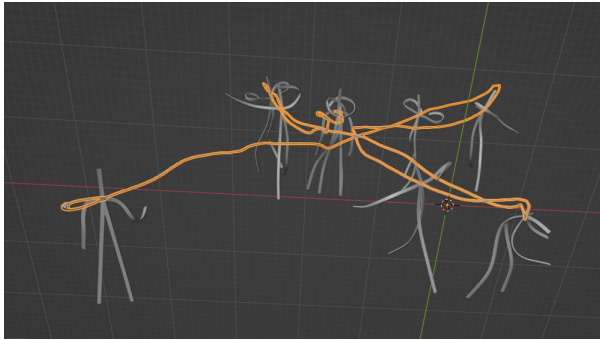
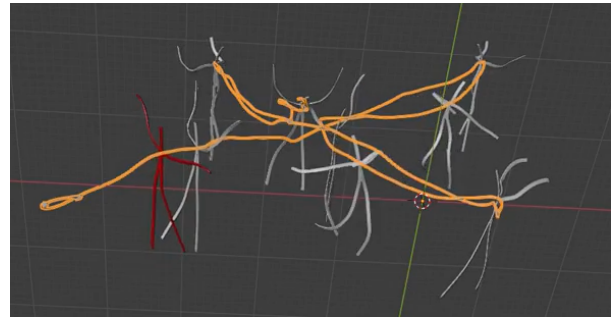


Figure 6.7 – Bending curve (in blue) and the extracted peaks (in orange) for the Prelude dance.



(a) Keyframes extracted from our algorithm



(b) Keyframes selected by Elisabeth

Lastly, since the keyframes are actually moments of impulses, one could improve the algorithm by defining the temporal length of the moment of impulse based on the thickness of the peak (the larger the peak, the longer the moment of impulse).

6.2.2 Creating the Prototype

To display the trajectory of the solar plexus, we displayed a 3D curve composed of all the positions of the plexus with respect to time, using a tube-like mesh to make it more visible. The tube was divided in smaller tubes in between moments of impulse, to be able to make them appear and disappear for *Prototype next keyframe*. Moreover for *Prototype three keyframes*, to be able to have the solar plexus line disappear as the red ribbon would have entered it, we sectioned the line into small cylinders between two time frames, and made them disappear as time goes by. Each moment of impulse was a small baked animation

that loops from the start until they disappear. They were all synchronized to that they exactly coincide with the red ribbon as it enters the moment of impulse. I used the Blender software (Blender 2018) to generate the prototypes. To create the AR visualization, I used Unity (Haas 2014) and Microsoft MRTK².

²<https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/?view=mrtkunity-2022-05>



Sharing the Different Systems with Dancers

7.1 Method

We organized a workshop aimed at understanding how dancers perceive the three prototypes we co-designed and how the different attributes affect their learning and perception of Isadora Duncan's spatiality. To do so, we ran a structured observation (Garcia et al. 2014) comparing qualitatively how dancers experience each prototype.



Figure 7.1 – Participants performing the Prélude dance during the teaching process with Elisabeth



7.1.1 Procedure

The workshop took place in a local dance studio. First, Elisabeth led a 30 minutes warm-up session with the participants to invite them to warm up to the style of Isadora Duncan. Then Elisabeth taught the participants the Prélude dance for 15 minutes. Participants were then asked to fill in body maps to represent how they felt after that learning process (see Figure 7.3 to see an example of a filled body map). I then introduced how the Hololens 2 headset worked and showed participants a video of how to use the menu of the headset. Participants, as well as Elisabeth and my supervisor Sarah Fdili Alaoui, were then split into two groups: group A and group B, as shown in Table 7.2. In the first part of the workshop, each group was introduced to one of the two prototypes (*Prototype next keyframe* and *Prototype all keyframes*). Each group member had 10 minutes with the Hololens 2 headset to explore the prototype. After that, participants filled in body maps to document their embodied experiences of the prototype. We then held a group discussion for approximately 15 minutes, in which we asked them to verbalize their experience. In the second part of the workshop, we switched prototypes among the groups. Again each dancer had 10 min with the headset, filled out a body map, and participated in the following group discussion. Lastly, all participants were introduced to the last prototype in the Hololens 2 headset, each participant having 10 minutes to experiment with it. Table 7.1 shows the prototypes that each group experienced in each part of the workshop. We finished the workshop with a group discussion. During the group discussions, all participants, along with Elisabeth, Sarah Fdili Alaoui and myself sat on the floor to discuss the differences in the perception and experiences of the prototypes (see Figure 7.2).

7.1.2 Participants

We recruited four participants with previous experience with the Duncanian style through classes they took with Elisabeth. We name them *P1* through *P4*, as shown in Table 7.2. Elisabeth led the warm-up and the teaching of the Prélude dance. Then she participated in the experiment with the prototypes as other participants did.

I introduced the prototypes, set up the headsets, and took pictures and videos and did not participate in the experiment. My supervisor Sarah Fdili ALaoui, who is also a dancer and choreographer also took part in the workshop, like other participants. She will be referred to as *A2*. Both Sarah and I led the group discussions and participated in them in an organic way sharing our own experiences and observations with the other dancers.

	Prototype 1	Prototype 2	Prototype 3
Group A	<i>Prototype next keyframe</i>	<i>Prototype all keyframes</i>	<i>Prototype three keyframes</i>
Group B	<i>Prototype all keyframes</i>	<i>Prototype next keyframe</i>	<i>Prototype three keyframes</i>

Table 7.1 – Order of which groups of participants experienced which prototype.

Group name	Participant number
Group A	P1, P2, A2
Group B	P3, P4, Elisabeth

Table 7.2 – Participants distribution in groups.

7.1.3 Data Collection

We analyzed the body maps that the participants filled out. We also recorded the group discussion that happened after each exploration of the prototypes. We took pictures and videos of the participants. We also took personal note of interesting events and striking discussions.

7.1.4 Data Analysis

Both Sarah and myself analyzed the data. We transcribed the audio recording and analyzed the videos and pictures, as well as the handwritten notes and the body maps. The transcribed data was then analyzed using a thematic analysis approach: we tagged concepts using codes (open coding) and then reorganized them into themes (axial coding) (Guest et al. 2012).

7.2 Findings

7.2.1 Different Systems for Different Perceptions

7.2.1.1 Perceiving Duncan's Qualities

Participants discussed how the different prototypes (*Prototype next keyframe*, *Prototype all keyframes*, and *Prototype three keyframes*) let them perceive the qualities of Duncan's





Figure 7.2 – Participants discussing their feelings during a group discussion.

dance differently. For example, they mentioned that they perceived the initiation of the movement from the solar plexus differently in each prototype that they experienced. They also perceived the relationship to gravity differently in each prototype.

For *P4*, the initiation from the solar plexus was visible in all three prototypes: “*For the plexus, it is really good we feel it really well*” (*P4*). Indeed the blue line tracing the trajectory of the solar plexus was enough for them to see how central this part of the body is in the style of Isadora Duncan. However, participant *P1* perceived the initiation from the solar plexus mainly in *Prototype three keyframes*. This was due to the fact that the red ribbon was not visualized but also to the fact that the blue line disappeared as the dance was performed. This puts emphasis on *P1*’s relationship to her own solar plexus, encouraging her to move as the blue line disappeared with time: “*For me it was really different, I really felt, [...] how to have the movement coming from the solar plexus, and there it is really motivated by here (pointing to her plexus)*” (*P1*). She compared it to the other two prototypes (*Prototype next keyframe* and *Prototype all keyframes*), and described how only *Prototype three keyframes* let her feel how the plexus is the source that leads the movement “*I told myself I was going to follow the blue line. And then I really felt it, the movement motivation. Yeah. With the other ones, I didn’t have that at all.*” (*P1*).

Participant *P2*, on the other hand, thought that in *Prototype three keyframes*, she did not see the movement of the solar plexus as she did in the other prototypes through the articulated motion of the red ribbon. Instead, in *Prototype three keyframes*, she saw the displacement and the trace of the movement as visualized through the disappearing blue line of the plexus: “*It’s almost the opposite for me because I find that the progress of the*

plexus is so strong on the first and the second one [referring to Prototype next keyframe and Prototype all keyframes], that here [referring to Prototype three keyframes] I mainly felt the displacement, and way less the movement of the body, the trace in fact, the displacement in the trace on the ground.”(P2).

However, dancers reported that all the prototypes did not let them see the grounding of the feet, creating a fracture between the upper body and the lower body: “*This is maybe what bothers me the most, we have the feeling that they are weightless, whereas when we dance we are looking for grounding, and that inconvenience that I was feeling is really [because of] that. There’s a fracture between the two, between that weightlessness that we see or feel through vision and this need that we have to be grounded. I don’t know, I am a bit lost with that.*”(P2). This was already a problem raised in our study described in Section 5.2, it is not surprising that the dancers mentioned it again. This limitation echoes what was found in the literature as the relationship to the ground remains a problem in computer graphics when displaying an animation reconstructed from motion capture (Basset et al. 2020).

7.2.1.2 Perceiving Spatiality

Participants had different perceptions of the augmented space in each of the prototypes that they experienced.

After her first experience with the headset (with *Prototype all keyframes*), participant P3 pointed out that she felt more aware of the general space, as shown on their Body map in Figure 7.3 where she wrote “*We are more aware of space*”(P3). She wrote it next to the eye area, which she also highlighted in color. This shows how the perception of space in the system was mostly visual.

Participant P2 felt like *Prototype all keyframes* helped her see the depth of space more than *Prototype next keyframe*: “*What I really like with the second one, but maybe it’s because I saw it in second, is there is all this depth of space, whereas the first one flattened space. We are just in the space of the moment. I think that with Duncan, there is a momentum really far away. And it’s there where we have all this projection [referring to all the keyframes in space], and I think we can enter it without stumbling*”(P2). Seeing all the keyframes placed in space until the end of the choreography helped P2 comprehend how the choreography was articulated in space, letting her “enter” the keyframes without “stumbling”, as opposed to *Prototype next keyframe* where only the next keyframe is displayed along with the next section of the trajectory of the solar plexus. Elisabeth also pointed out how *Prototype all keyframes* let her see the “globality” of the movement and the duration of displacements: “*And so I felt better the duration of the displacement. Which I never felt through the previous steps. I think we end up tasting, for someone who would like to learn*



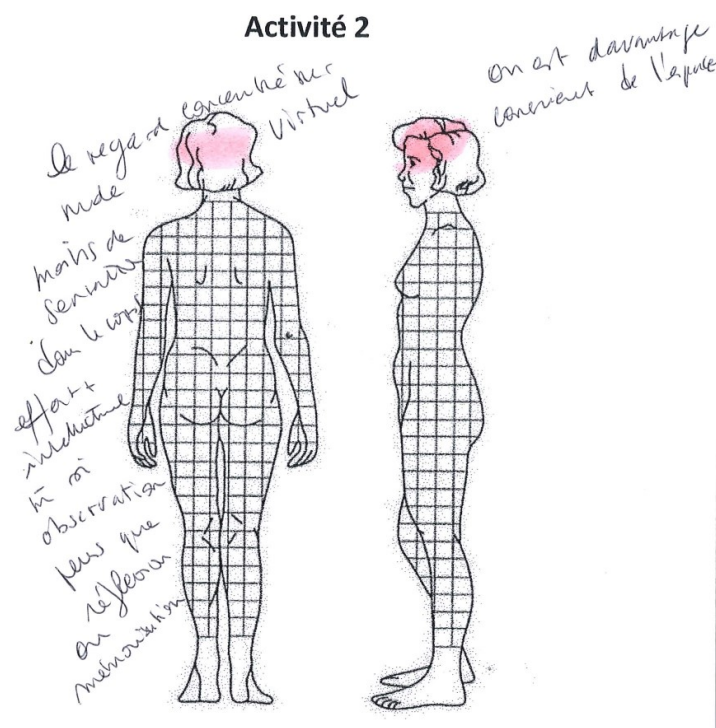


Figure 7.3 – Body Map filled by P3 for their experience of *Prototype all keyframes*. Participant highlighted the eye area and wrote “we are more aware of space”.

the dance, to have a taste of the displacements”(Elisabeth).

After her experience with *Prototype next keyframe*, participant P4 pointed out how the direction and orientation of the dance were clearer than with the previous prototype (*Prototype all keyframes*). Seeing fewer keyframes allowed her to focus on the directionality and orientation of the body rather than the general spatiality of the piece. In her body map shown in Figure 7.4, P4 scribbled the word “direction” as a significant element brought by her experience of *Prototype next keyframe*.

7.2.1.3 Less is More

Participants also pointed out that the less information they had, the better they could focus on Duncan movement qualities. For instance, Elisabeth preferred to start with *Prototype next keyframe* than with *Prototype all keyframes* because it had less information, letting her focus on one aspect of the dance: “*For us, it was complicated, the first time, to have all the complexity of the poses, the trajectories, in fact I think it’s more simple when we use the second one [referring to Prototype next keyframe], that is only the next one*”(Elisabeth).

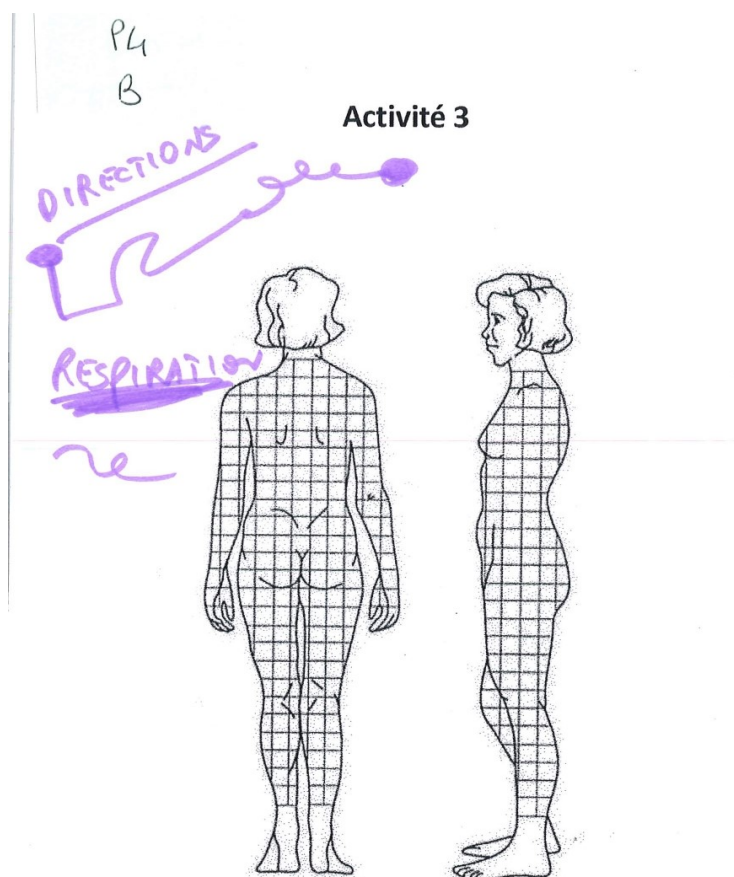


Figure 7.4 – Body Map filled by P4 for their experience of *Prototype next keyframe*. Participant wrote “directions” as well as a doodle of a trajectory. They also wrote “breathing”.

Another participant pointed this out for the *Prototype three keyframes* compared to the first two prototypes. She said: “*There is also the fact of having less information on the third one [referring to Prototype three keyframes]. On the other two, I really had the feeling of having a lot of information at the same time, and it feels good to have a little bit less. To focus on one thing.*”(P1). Having less information enables dancers to focus on specific qualities. Too many keyframes displayed in space overwhelmed them with too much information that they did not need. This was particularly the case if the multiple keyframes prototype was the first that they experienced. The dancers needed to start with little information and build up layers of complexity as they progressed in the dance.



7.2.2 Different Systems for Different Actions

The three systems that we proposed led to a variety of bodily responses from the dancers, ranging from observing to marking to improvising with the system.

7.2.2.1 The System as a Way to Engage Users to Observe

After exploring the two first prototypes (*Prototype all keyframes* and *Prototype next keyframe*), 3 participants agreed that they felt best when observing the system and not moving in space: “*If we don’t enter the movement, we perceive the choreography really well, we feel it, we see how the body moves, it’s surprising, with only three lines.*”(P3). Two out of four users expressed frustration because they wanted to engage with the system, but the visual information was “too much”, particularly in *Prototype all keyframes*. “*My first reaction was it’s really frustrating, to see it without accompanying it, what we want to do is to accompany it, to enter in its movement, yeah really to enter in its movement, but when we do that we lose it almost instantly, we get it only for a few moments*”(P2). Dancers refrained from moving because when they did, they lost track of the red ribbon and of the future keyframes displayed. This is partly due to the learning that participants had to go through to comprehend the technology of the headset and the way the system was designed in space. Moreover, this is also due to the fact that in both *Prototype next keyframe* and *Prototype all keyframes*, moments of impulse disappeared as the red ribbon entered them, causing the dancers to feel as if they lost track of the ribbon.

7.2.2.2 The System as a Way to Engage Users to Mark

One participant started marking the dance when exploring with *Prototype next keyframe*. When asked if she moved with it, she answered “*No, not really dancing but... I marked*”(P4). Marking consists of performing the movement in a less complete manner. We observed the dancers imitating the movement with one hand or performing it with the full body but with less energy. They marked with their bodies the movement while observing the ribbon enter the keyframes as a way to engage physically in the learning while keeping track of the system. Moreover, all dancers reported that they were encouraged to mark the movement because dancing it fully was not possible due to the cumbersomeness of the headset.

7.2.2.3 The System as a Way to Engage Users to Embody

Participants (3/4) noted that the third system (*Prototype three keyframes*) let them engage more significantly with the body in the dance than the two other prototypes: “*And the second time, because I did it twice, I told myself I was going to follow the blue line [...] With the other ones, I didn’t have that at all.*”(P1). P3 also reported that *Prototype three keyframes* helped her engage more in the dancing than the two previous prototypes that she experienced before (*Prototype next keyframe* and *Prototype all keyframes*): “*We are more in the movement perception, more to do the movement than to observe it.*”. Participant P3 also expressed that in her body map as shown in Figure 7.6. We can



Figure 7.5 – One participant dancing with the headset on.

see how when experiencing with *Prototype next keyframe*, her experience was mainly to observe. In contrast, when using *Prototype three keyframes*, she reported how she followed the movement of the “blue line” with her own solar plexus. In this prototype, the blue line is more visible because no red ribbon is dancing in space. The body of the participants becomes the dancing ribbon. All participants mentioned that they tried to superpose their plexus’s movement to the blue line in *Prototype three keyframes* as if their body produced it. They reported that doing that helped them engage in the dance and move with the blue line: “*For me, I really followed the blue line, and I really tried to follow it inside, to put myself in the spot of the figures, well of the red figure*”(P4).

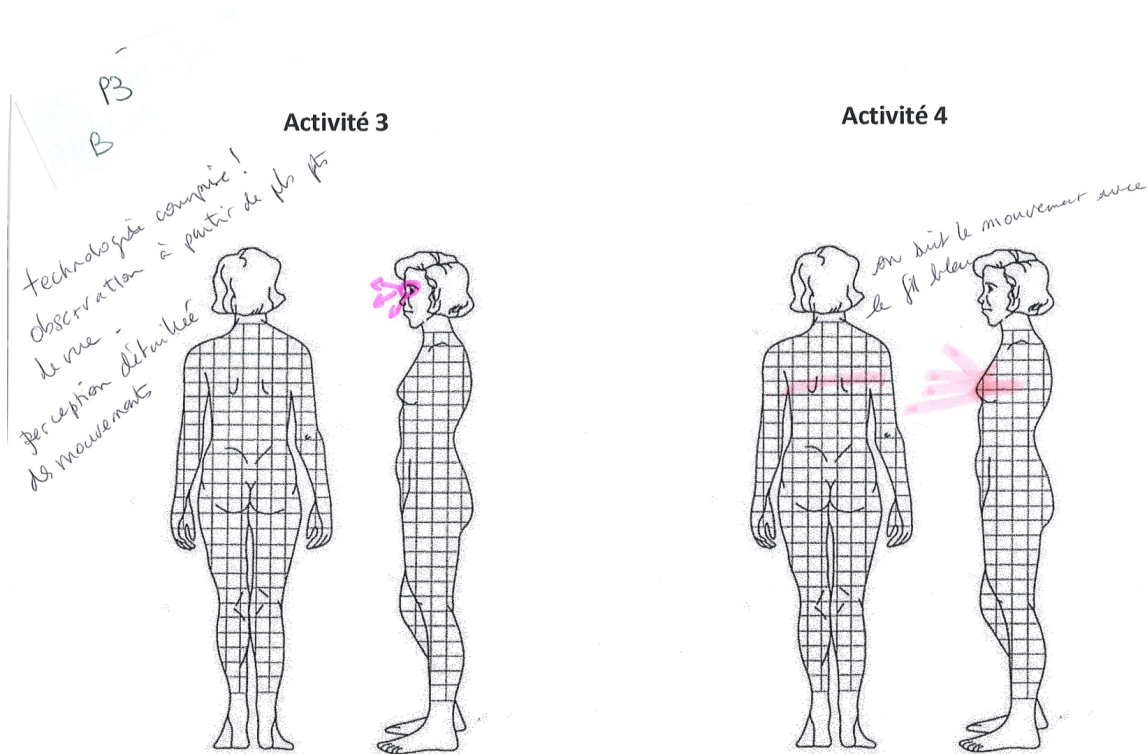


Figure 7.6 – Body Map filled by P3, on the left experience with *Prototype next keyframe*, on the right with *Prototype three keyframes*. On the left, participant drew arrows coming from the eyes and going in different directions. On the right, they drew lines coming from the solar plexus and going in different directions.

7.2.2.4 The System as a Way to Engage Users to Improvise

One participant (P2) went further with the *Prototype all keyframes*: she started improvising with each moment of impulse, forgetting about the original choreography. One of the participants said while watching her: “*She’s dancing with all the white ribbon. She’s creating her own choreography*”(P1). Another participant commented afterward: “*you looked really appeased. You were all serene.[...] Just like the Prélude*”(P3). We observed that during the improvisation, P2 was improvising with her own movement but borrowing from the style of Isadora Duncan. When asked about what she was doing during that improvisation, the participant said “*I was following the blue line. To have more landmarks.*”(P2). She then further explained that she was having a duet with each one of the keyframes in space: “*I was thinking it might be really interesting to work on duets. Because in the duo we are in a relationship that exists by itself. And so we can interact and learn to interact*”

with it. And see how we can interact with the one which exists by itself.”(P2).



Figure 7.7 – One participant improvising with the moments of impulse.

7.2.2.5 A Plurality of Systems for a Plurality of Experiences

At the end of the experiment, participants reflected with Elisabeth on how all the systems had something to teach. Indeed, rather than having one prototype that would fit all the needs, each prototype had something to bring in terms of their embodied experience: *“This is really complex, but this brings out the interest of having different “formulas” like we did today. Some very sober, very simple, it’s good because we can say, “ok I’m going to look at movement, the trajectory of the plexus, how do you have people see the ripple of the plexus, horizontal with suspension, going down to the floor, etc.” So you can learn something from each one of them.”*(Elisabeth).

7.2.3 Opportunities and Limitations of Augmented Reality

7.2.3.1 Learning Effect

Bringing a new type of technology to a dance studio was challenging. All participants experienced a learning effect that stopped them from truly experiencing the system’s po-

tential initially. “[...]it gives a bit of a headache. I don’t know why. Maybe it has something to do with habits. But it’s true that we see well, but it demands such a high level of focus, I don’t feel available to really follow it and to really be in it.”(P2).

Understanding where the model was in space and how it worked was also a challenge, “Yeah it is difficult for me to find the good position in space to see it in full because if I see only half of it is difficult”(P1). To resolve this issue, Elisabeth explained that she took a step back from the space of the studio to understand the space that the system was taking: “But in fact, looking at it a first time, well first there is the question of the technicality of the headset. I discovered that I had to take a few steps back to see better”(Elisabeth). AR headsets are indeed technologies that not many have at home. In the context of our workshop, the dancers were unfamiliar with the device and the interface. It took them some time to familiarize themselves with it. They also discovered during their second experimentation with the headset that the space that the system was evolving in was fixed, meaning that if they moved their head around the ribbons, the ribbons would stay where they were in the studio space and not follow their gaze: “And also I finally understood how the headset work. I thought that I was bringing it with me when I moved. But in fact, the figure exists in itself in space. I understand that I can turn, and I appreciate what I can do with it. And so I think I can really see the dance. From all side”(Elisabeth). This understanding of the spatial independence of the model in 3D also led to them positioning themselves differently in space, walking around the ribbons, and seeing it from different angles and perspectives.

7.2.3.2 A Tool to Enhance the Learning Experience

Despite the difficulties in familiarizing themselves with AR, dancers reported that they could see the potential of such technology. Elisabeth discussed how the different systems were an excellent way to practice a dance individually: “I like the trajectories etc. I think for someone who wants to learn it, they can look at it, then take off the headset; it’s a different experience of the dance, a more autonomous one”. Another participant also pointed out that it is a good learning tool “It’s really good to learn, I think, the choreography. To incorporate it. To see it like that”(P3).

Moreover, participants discussed the advantages of such a technology when learning. Participants noted that compared to a human body, the headset is more reliable in terms of energy and repeatability: “Yes, I think that this is tremendous. And I was also telling A2, the fact that we can also do it an infinite number of times without relying on a human body, which can get tired, or who doesn’t want to do it.”(Elisabeth). The headset not being human means it does not have the same needs and can be used repeatedly without needing breaks. Participant P4 even called it “economical” “It’s clear that it is economical,

it doesn't have to eat, to sleep"(P4). However, they all outlined that the system cannot replace a human teacher. Participant P1 pointed out that when she is lost in the dance, she had an easier time leaning on Elisabeth than on the red ribbons in the headset: "*It is a bit like looking at Elisabeth when we dance when we turn, and we're all together and I don't see her anymore. It's normal but also it is easier to find her back than to find the red stick figure.*". Another participant stated that she could not learn from that system alone: "*For me I wouldn't be able to learn the choreography with only this.*"(P4). All participants reported that the system would not replace a teacher but would complement the teaching by adding information. It also presented a potential for individual training beyond the class environment, for instance at home.

7.3 Discussion

7.3.1 Complementarity: Beyond One System for All

Our findings showed that removing the red ribbon and making the blue line disappear with the progression of the dance in *Prototype three keyframes* made the dancers engage with the system in a more embodied way and perceive the displacement of the solar plexus more clearly. The gradual disappearance of the blue line emphasized the trajectory of their solar plexus as a source of the movement. Dancers used this disappearing line as a *feedforward* that guides their movements from their solar plexus, making it the motor of their motion in space. We also observed how they started dancing with the *Prototype three keyframes*, imagining their own body (in the place of the red ribbon) as what produces the blue line. **This suggests that creating a virtual alter ego displaying a body dancing is not necessarily desirable as it might hinder the dancers' embodied engagement. In contrast, erasing the bodily representation in the augmented world seems to hold great potential for the dancers to use their bodies creatively. Additionally, our results show the potential of feedforward to guide dancers in performing movements.**

In terms of the perception of space, dancers could perceive the dance's globality better and acquire a better awareness of the spatial structure of the dance in *Prototype all keyframes* that displayed all the future keyframes. In *Prototype next keyframe*, because only the next keyframe is displayed, they were able to focus better on the orientation of the body in space. These two prototypes encouraged observation or marking of the movement but not dancing with the system. The reason for that is the amount of information displayed and the presence of a dancing red ribbon that invited dancers to look at it carefully. We were able to see, however, how one of the dancers appropriated the *Prototype all keyframes* by improvising with all the future white keyframes as if they were characters in their own



right.

Thus, the results of our study showed that there is no clear way to state that one prototype was better than another in fulfilling all the dancers' needs. Although *Prototype three keyframes* seemed to engage the dancers in more embodied ways than the other prototypes, *Prototype all keyframes* gave an idea of the overall duration and spatiality of the dance, and *Prototype next keyframe* provided minimal information that allowed the dancers to focus on one aspect of the dance as they progressed in their learning.

Offering a multitude of options to the dancers came up in our discussions with the dancers as something that can benefit them at different stages of their learning experience. This would allow them to experiment with various features according to their needs. Because learning is not a linear action, but rather an evolving experience that requires adapting and shifting one's strategies (Rivière et al. 2019), **we see the value of designing systems that complement each other rather than one system that fits all needs and desires.** Complementarity can also allow for more gradual learning of the new technology. Dancers can start experimenting with a few features and later layer them with more complex ones as they become more familiar with the newly added ones.

7.3.2 Potential of Augmented Reality in Dance Education

When choosing how to display our system to the dancers, an AR headset like the hololens 2 felt like a good option. Echoing the guidelines formalized by Raheb et al., we found that AR has good potential in dance education because it relies on portable headsets that can be brought to a dance studio. This allows the dancers to experiment with the technology in their familiar environment instead of in a non-ecological environment such as a lab (Raheb et al. 2019). Additionally, AR allows visualizing information in 3D, augmenting the regular space of the studio with additional feedback and guidance for the dancers. Finally, dancers reflected on the potential of using AR devices as learning support in addition to the human teacher. They identified the advantages of such technology in that it can be used repeatably without tiring and in various contexts, such as the home or outside. Thus, using AR brings a sense of independence to dancers who want to learn a new dance style on their own terms.

However, we found that bringing such a novel and unhabitual piece of technology to the dance studio is challenging. Dancers have been trained using the body solely for decades, and altering the body with a headset is cumbersome and difficult to adapt to. Moreover, the headset hasn't been designed for this kind of usage. When performing, dancers usually need to move their heads which is something they can not do easily with the headset. We observed how dancers feared letting the headset fall to the ground and adopted a more cautious embodied behavior. Moreover, the headset is not made to be used in a dance

studio where the lighting is not ideal for the AR technology to work perfectly.

Overall, our findings do not suggest that AR technology can replace a human dance teacher. Instead, they highlight how AR can support students in learning different aspects of dance without depending on official classes to have access to training. Additionally, using AR could be promising for non-dancers who do not dare to enter a dance studio to take a class. When trying it at the lab with different researchers, we saw how we could reach a wider audience, who, by testing the AR headset, ended up learning about the philosophy of Isadora Duncan and even trying to dance with it when they did not know of the dance in the first place.



Part III

**How can the Ribbon Model be used
to Transfer a Dance Animation from
one Animated Character to Another?**



Résumés en français des chapitres

Chapitre 8

Dans ce chapitre, nous nous intéressons au transfert d'animation d'un squelette articulé à un autre, ayant une morphologie ou une topologie différente du squelette source. Nous nous concentrons sur le transfert d'animation de mouvement de danse. Le système que nous avons créé prend en entrée des données de capture de mouvement d'une danse et les transfère à un autre corps qui peut avoir une morphologie différente. Pour ce faire, nous générons d'abord des rubans à partir des données de capture de mouvement (squelette animé ou ensemble de marqueurs). Ensuite, nous associons chaque ruban à une chaîne articulée du squelette cible. Enfin, nous appliquons l'animation contenue dans les rubans sur le squelette cible à l'aide d'un algorithme d'optimisation.

Chapitre 9

Dans ce chapitre, nous menons d'abord une réflexion sur le processus de co-conception avec notre danseuse experte, qui a duré 3 ans, où nous soulignons la richesse d'une telle méthodologie de recherche dans le but de concevoir des outils. Nous réfléchissons également sur le besoin impérieux de créer des liens entre les disciplines du graphique 3D, de l'interaction humain-machine et de la danse. Ces disciplines, bien que proches, ont souvent du mal à collaborer. Nous discutons aussi des différents travaux futurs qui pourraient suivre ces travaux de thèse, comme se concentrer sur les pieds, tester les prototypes avec des utilisateurs non danseurs afin de mesurer leur efficacité. Enfin, nous abordons l'impact écologique des travaux menés et le manque de recherches traitant de l'impact de l'utilisation des technologies de réalité augmentée et virtuelle sur les utilisateurs et l'environnement.



Dance Motion Retargeting using Ribbons as a Line of Action

In the previous chapters, we described the results of the co-design process with Elisabeth Schwarz. In this chapter, we describe a piece of work that was not co-designed with Elisabeth. Instead, we explore a new application of the ribbon model. This chapter describes ongoing work.

8.1 Inspiration

We were inspired by the work of (Guay et al. 2013). In their work, they use *The line of action*, a 2D curve used by cartoonists to help draw the first shape of expressive motion. This hand-drawn line is used to help with character posing by matching the line to an articulated chain going from one extreme to another called a *body line*. In their following work, they use the speed at which the user draws the line of action to help pose the character through time and, therefore, animate it (Guay et al. 2015b). In our case, we can see that the ribbons generated in Chapter 4 are 3D curves containing the original motion’s poses. Those curves could be used in the same fashion as a spline IK (Autodesk 2009). A spline IK provides the ability to manipulate a chain of joints using a spline curve. All the joints influenced by the spline IK handle remain attached to the curve. Additionally, the spline IK offers extra attributes, including twist, that allows for additional control over the orientation of the joints. Similarly, the line of action is used to move an animated skeleton. Since we have one ribbon per time frame, performing a similar optimization process for each time frame leads to transferring the initial animation to a new articulated skeleton.

Transferring an animation from one skeleton to another is a well-known problem in computer graphics called motion retargeting. In motion retargeting, the goal is to animate a skeleton, which we will call the target skeleton, from motion contained in another animated skeleton, which we will call the source skeleton. Because there is no guarantee that the source skeleton and the target skeleton have the same topology or morphology, the question is, how to transfer that animation from the source skeleton to the target skeleton?



In our specific case, our goal is to transfer the *dance* movement of Isadora Duncan from one animated character to another. In dance transmission, and especially with Isadora Duncan’s movements, two of the most essential aspects of the movement when transferring it to another body are the overall shape of the body and the inherent qualities of Duncan’s dance movement (defined in Chapter 3). As discussed in Chapter 5, the ribbons can capture the essence of the Duncanian movements, making abstraction of the morphology of the recorded dancer. We hope that by using the ribbon model to transfer the animation, the essential qualities of Duncan’s movement will remain.

8.2 Overview

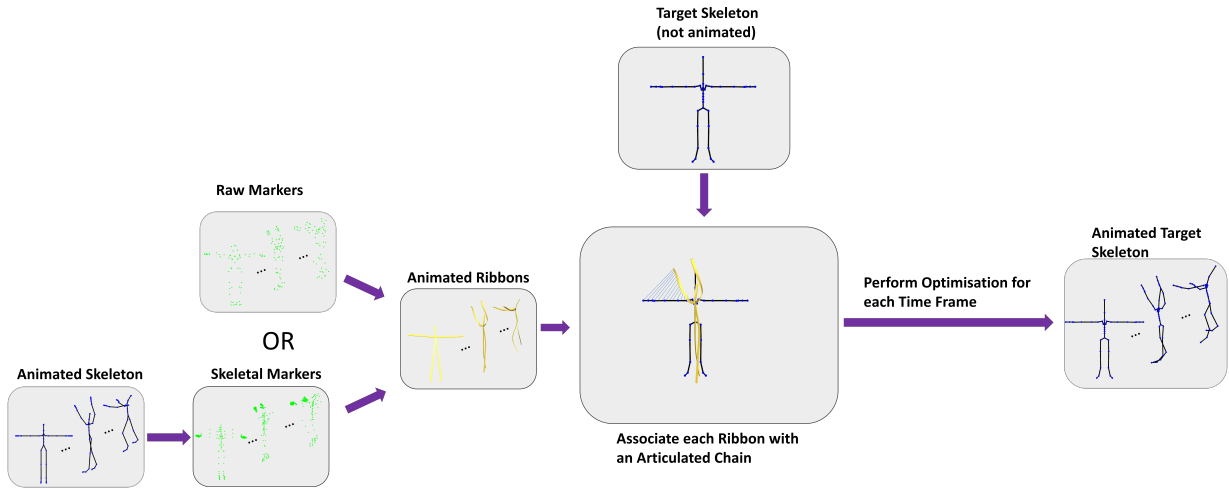


Figure 8.1 – Overview of our proposed method.

An overview of our proposed method is described in Figure 8.1. The first step of our method is to generate the star-shaped ribbon as defined in Chapter 4. As Section 4.1 explains, the ribbons can be generated from raw 3D marker positions or an animated skeleton. The input is a set of 3D markers from raw motion-capture or skeletal data. Then, we manually associate each ribbon with an articulated chain of the target skeleton. An *articulated chain* is defined as a set of connected bones, each bone being connected to one or two bones. Using springs, we then link each vertex of the ribbon to a corresponding point on the corresponding articulated chain. The springs’ rest lengths are defined when the ribbons and the target skeleton are in a T-Pose. Then, we use an optimization process at each time frame to minimize the summed energy of all springs connecting ribbons’ vertices and their corresponding points on the articulated chain. This optimization process yields the corresponding pose of the target skeleton at each time frame. The output is then the resulting animated target skeleton. In the optimization process, the variables are the

3D positions of the skeleton's joints. As the process of animating ribbons from motion-captured data is already described in Chapter 4, we only need to describe the process of animating a skeleton from our animated ribbons.

8.3 Animating a Skeleton from a Ribbon

We first manually select what part of the skeleton is affected by each animated ribbon (see Figure 8.2b). Let us recall that a ribbon is defined as a rod made of a set of vertices $(x_i)_{i \in [0, n+1]}$ and a set of frames $M^i = \{t^i, m_1^i, m_2^i\}$, defined with respect to a Bishop frame $B^i = \{t^i, u^i, v^i\}$. In the following section, we will keep the same notations as the ones introduced in Chapter 4.

8.3.1 Preprocessing the Ribbons

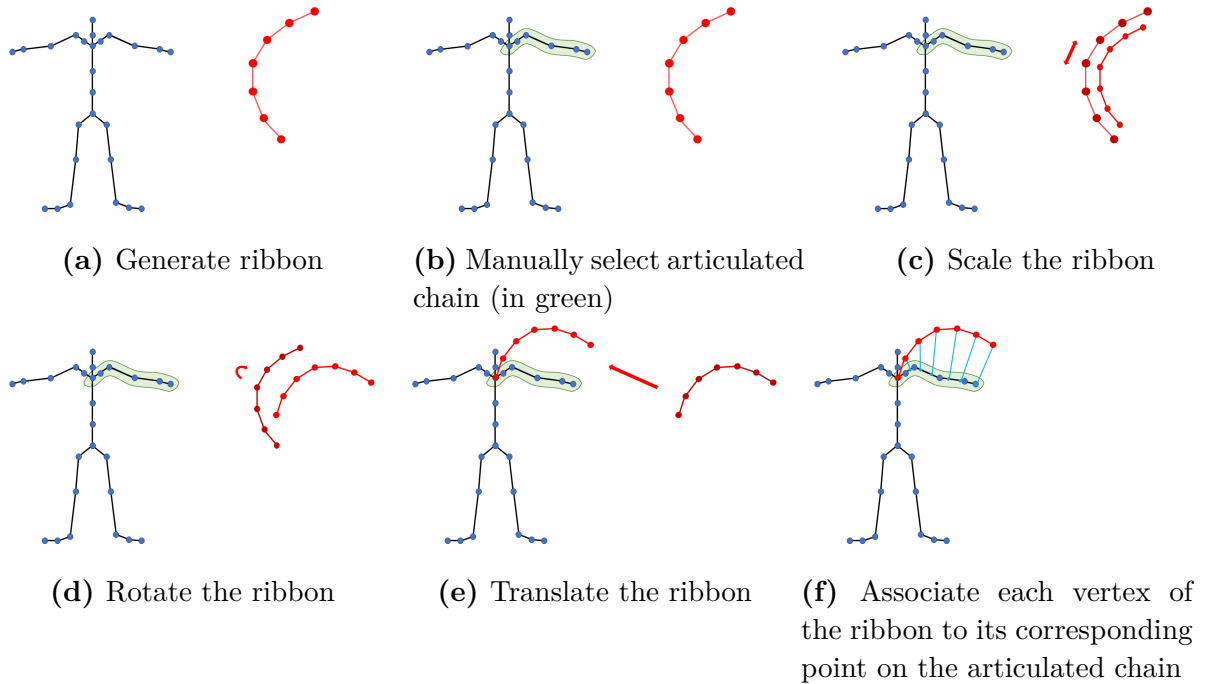


Figure 8.2 – Steps of pre-processing the ribbon and initialization of the cost function.

The ribbon is not guaranteed to be the same size as the chosen articulated chain. Therefore, we uniformly resize the ribbon to the length of the articulated chain at rest (that is, we keep the ratios between edge lengths). When evaluating the rest length of the springs connecting the ribbons' vertices to their corresponding point on the articulated chain,



there is also no guarantee that the orientation and position of the ribbons are close to the desired articulated chain. To guarantee closeness, we first generate a ribbon, which we will call *articulated chain ribbon* from the selected articulated chain during the T-pose, using the algorithm defined in Algorithm 1, and using the joints of the articulated chain as marker input, as well as the virtual markers as defined in Section 4.1 and Figure 4.2b and 4.2d.

We then evaluate the translation between the *articulated chain ribbon* and the animation ribbon by evaluating the translation between their solar plexus. After the translation is performed, the rotation between the ribbons is defined as the rotation of minimal angle that aligns the animation ribbon to the *articulated chain ribbon*. As the ribbons are in a rest state and are straight 3D segments, this rotation can be seen as the parallel transport of the animation ribbon to the *articulated chain ribbon*. We then store this initial rotation.

Scaling, translation, and initial rotation are applied to the animated ribbons across all time frames. The translation vector is evaluated at each time frame, whereas scaling and initial rotation are evaluated during the T-pose. Algorithm 3 shows the pre-processing steps and the initialization of the rest states of the springs.

```
input : Set of markers
output: Initialized optimization system
Generate ribbons (Figure 8.2a);
for each ribbon do
    Select articulated chain (Figure 8.2b);
    for each time frame do
        Resize ribbon to the length to the articulated chain (Figure 8.2c);
        Rotate according to generated ribbon from mocap data (Figure 8.2d);
        Translate ribbon according to generated ribbon from mocap
        data (Figure 8.2e);
    end
    Associate vertices with corresponding positions along centerline (Figure 8.2f);
    Evaluate the rest state of the springs;
end
```

Algorithm 3: Preprocessing the ribbons and Initializing the retargeting system.

8.3.2 Creating the Energy Function of the Optimization Problem

8.3.2.1 Shape Energy Function

To ensure that the shape of the articulated chain will be as close as possible to the shape of the ribbon, we associate each vertex of the ribbon to the point on the articulated chain with the corresponding arc length position using springs. That is, the i^{th} vertex on the ribbon arc length position is $\frac{i}{n+1}$, $i \in \llbracket 0, n+1 \rrbracket$ (because the generated ribbon is discretized regularly). Therefore, we associate the corresponding point on the articulated chain with the arc length position of $\frac{i}{n+1}$. Let us denote this point w_i (see Figure 8.3).

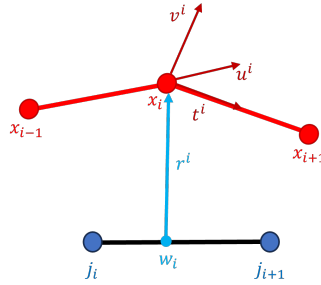


Figure 8.3 – Schema showing the relations between a vertex x_i from the ribbon and the associated point on the articulated chain w_i .

This point belongs to a bone. Let us denote b_i the bone in which it belongs, and j_i, j_{i+1} the joints/extremities of the bone. We can express w_i with respect to the joints using barycentric coordinates:

$$w_i = yj_i + (1 - y)j_{i+1}, \quad (8.1)$$

where $y \in [0, 1]$. To associate the vertex to the associated point, we define the vector as:

$$r^i = x_i - w_i. \quad (8.2)$$

In order to keep the natural angles (i.e., angles when in a T-Pose) of the target skeleton through time, we lock the vector r^i in the Bishop frame B^i associated with the edge e^i . To do so, we first recall that since the Bishop frame is an orthogonal basis of \mathbb{R}^3 , we can write

$$r^i = (r^i \cdot t^i)t^i + (r^i \cdot u^i)u^i + (r^i \cdot v^i)v^i. \quad (8.3)$$

To lock the vector r^i in the Bishop frame, we aim at maintaining the coordinates in the Bishop frame basis as constant as possible, which means the energy function for one vertex x_i

$$E_{springs}(x_i) = ((\overline{r^i} \cdot \overline{t^i}) - (r^i \cdot t^i))^2 + ((\overline{r^i} \cdot \overline{u^i}) - (r^i \cdot u^i))^2 + ((\overline{r^i} \cdot \overline{v^i}) - (r^i \cdot v^i))^2 \quad (8.4)$$

needs to remain as minimal as possible through the animation. To obtain the total spring energy, we sum this energy over all vertices of all ribbons.



8.3.2.2 Enforcing the Bones Constraint

In a rig-based animation, the length of the skeleton's bones remains constant throughout the animation. This inextensibility constraint can be translated into a strong stretch energy of the bone b_i :

$$E_{stretch}(b_i) = \alpha(\|\bar{j}_i - \bar{j}_{i+1}\| - \|j_i - j_{i+1}\|)^2, \quad (8.5)$$

where b_i is the bone connecting joint j_i and j_{i+1} and α the stretching coefficient. The total energy to enforce the inextensibility of the bone is then obtained by summing over all bones in the skeleton. The final minimization problem is then:

$$\min_{b_i \in skeleton} \sum_{ribbons} \sum_{i=0}^{n+2} E_{spring}(x_i) + \sum_{bones} E_{stretch}(b_i) \quad (8.6)$$

We then run an optimization algorithm on this cost function to find the 3D position of each joint. As opposed to the generation of the ribbons, where each ribbon is generated independently from one another, we create *one* optimization problem that takes into account the total energy over all ribbons associated with the skeleton's articulated chains. This optimization process enables us to find the optimal position of the skeleton at each time frame. Algorithm 4 describes the retargeting steps.

```

input : Markers and Target skeleton
output: Animated skeleton
Generate animated ribbons;
for each ribbon do
    | Pre-process ribbon;
    | Initialize cost functions;
end
for each time frame do
    | find the optimal position of target skeleton joints  $j_i$ ;
end

```

Algorithm 4: Retargeting Steps.

8.4 Results

Figure 8.4 shows the input ribbons and two skeletons with different topologies retargeted using our algorithm in different poses of the Prelude dance. This first result show that the proposed method is able to retarget the animation and that the shape of the input ribbon well transferred to the target skeleton. However when looking at the animations, there are some instabilities around the feet area. This is due to the fact that when generating the ribbons, we do not take the feet markers into consideration, but we did associated the feet joints to the ribbons.

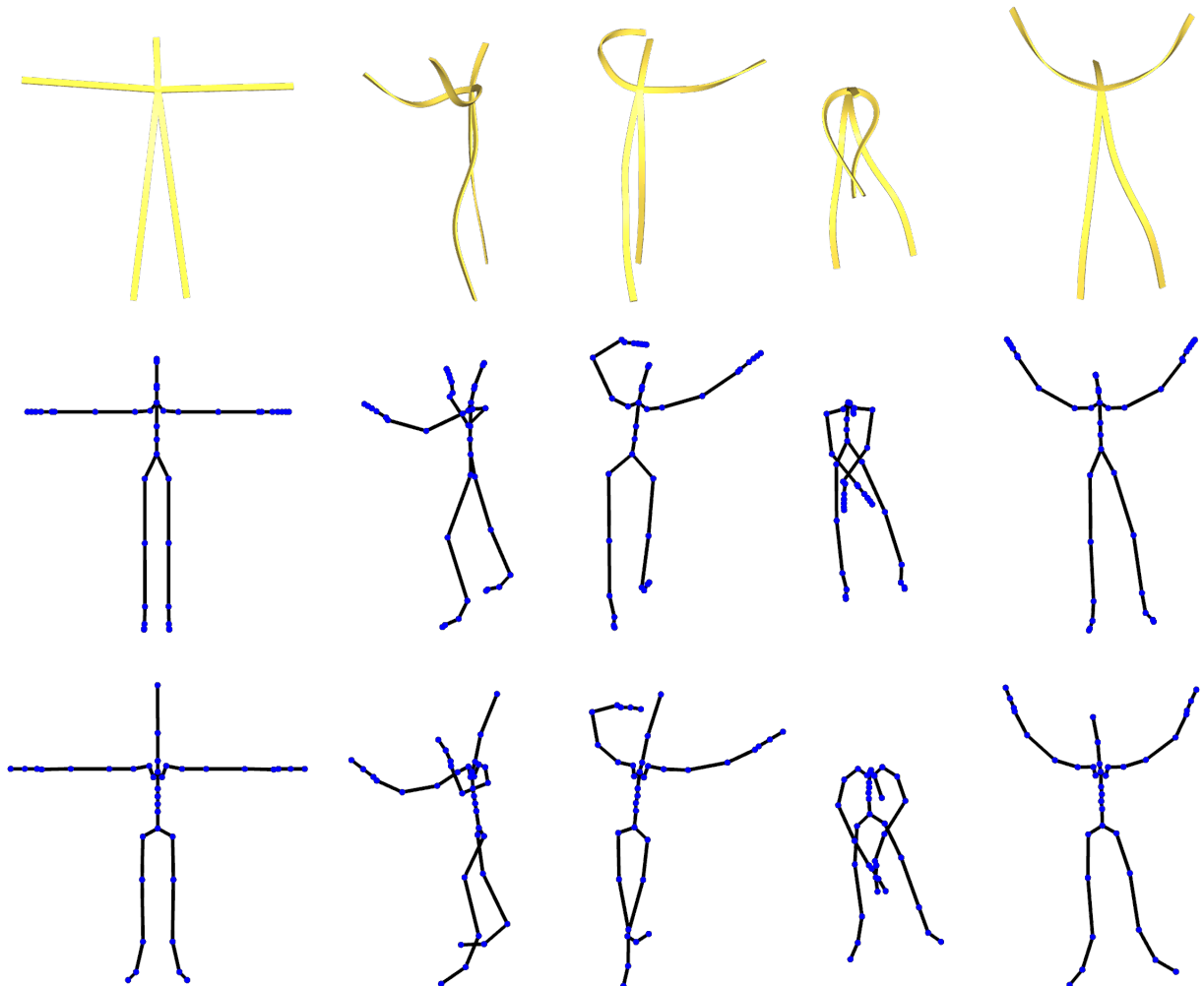


Figure 8.4 – From top to bottom: input ribbon, retargeted humanoid skeleton with the same morphology as the input data, retargeted skeleton with added bones and different T-Pose shape.



8.5 Future Work

8.5.1 Evaluating our System

In future work, we want to run a study to evaluate whether the resulting animation is realistic and authentic to the style of Isadora Duncan. A first evaluation would be to use our retargeting system with the same input and target skeleton. Then, we could evaluate the distance between the two animations by evaluating the mean square error between the joint positions. Moreover, a more qualitative evaluation could take place to evaluate which animation is closer to the style of Isadora Duncan.

When looking at input and target skeletons with different morphologies or topologies, it can be quite difficult to evaluate the results of a retargeting algorithm because there is usually no ground truth to the problem. In (Abdul-Massih et al. 2017), they argue that the best way to evaluate the "naturalness" of a resulting motion is to run a test study with users, showing them the animation and asking them three types of questions:

- asking the participant if the motion presented to them is a real motion or a computer-generated one
- showing participants one motion created by an animator and one retargeted motion, and asking them which of two motions is the most realistic
- ranking naturalness of the motion on a scale of 1 to 10

However, in (Aberman et al. 2020), they compare their results to a ground truth from the *mixamo* motion database (Adobe 2003) by evaluating the average error over all joints and all motions. This animation database contains animated skeletons with various morphologies and topologies for each animation. However, it is not clear how the animation was transmitted throughout all the different characters and topologies. Moreover, each animation is relatively short compared to our recorded dances.

A good validation of our proposed method would entail a user test study on Isadora Duncan's retargeted dance and evaluating errors between ground truth and generated motion on the *mixamo* database.

8.5.2 Extension of the Method

In future work, we could adapt our algorithm to ribbons that have been generated with different topologies than the star shape designed in Chapter 3. Different topologies for the

ribbons could help retarget the skeleton with more diverse topologies. Figure 8.5 shows possible topologies of the ribbon. Lastly, since the ribbon encaptures the motion qualities

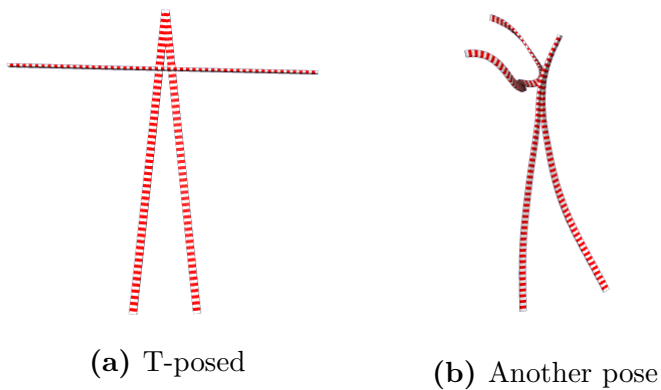


Figure 8.5 – Different topology for the ribbons: A shape.

of Isadora Duncan, we could investigate if the ribbons could be used in the problem of motion style transfer.



Discussion

In this Ph.D. thesis, we followed a three-year-long co-design with a connoisseur process with Elisabeth Schwartz and an expert dancer in Isadora Duncan's style. During this process, we first outlined three main qualities of Isadora Duncan's dance style: the wave, the solar plexus, and fluidity. To transmit those qualities, we created a new abstract model to represent a dancing body tailored to Isadora Duncan's style. This model is made of 5 flexible ribbons joined together at the solar plexus and is animated from motion-captured data using a tailored optimization process. We evaluated this model with dancers in an augmented reality headset and found that it faithfully represents the specific qualities of Isadora Duncan's style. Based on the feedback of the dancers, we co-designed with Elisabeth a new system that aims to enhance the perception of spatiality for dancers in augmented reality. To do so, we were inspired by the Sutton dance notation. The systems visualize the ribbons performing Isadora Duncan's dance, along with animated keyframes, which we call moments of impulse, and the trace that the solar plexus leaves in space. We ran a structured observation to evaluate the differences in the number of keyframes displayed simultaneously. We found that there is not one system that fits all needs but rather a variety of systems for a variety of uses. Moreover, dancers highlighted how augmented reality has great potential for pedagogical purposes. Lastly, in an ongoing work, we were inspired by the ribbon model and the line of action to create a system that transfers a dance motion from one animated skeleton to another.

In this chapter, I will discuss some of the main aspects of our work and highlight new opportunities for improvement in future work.

9.1 Reflection on the Co-design Process

9.1.1 The Value of Co-designing with a Connoisseur

Elisabeth has been a collaborator and co-designer of our systems from the beginning. She was curious about how technology could support the dancers' learning of Duncan's vocabulary. She expressed her interest and enthusiasm about representing the dancer's body in



an abstract way and augmenting the studio space with virtual elements representing the qualities of the movement and the spatiality of Isadora Duncan's work. Her knowledge of the dance was built over four decades of learning this repertoire and transmitting it to other dance artists. She dedicated all her career to building a deep understanding of Isadora Duncan's work. She used her knowledge in accompanying every step of the project. She infused ideas into the design of the systems. She gave feedback on the system at every stage of its design and development. She demonstrated the movements when necessary and tested the prototypes with her own body. She accompanied the design and organization of the workshop that we ran. Moreover, she taught me and my supervisor Sarah Fdili Alaoui the vocabulary of Isadora Duncan during multiple regular dance classes. I believe that such collaboration putting at the center the expertise of a connoisseur is fundamental in the design of technologies to support dance and kinesthetic creativity (Schiphorst 2011). Moreover, we value design approaches that dig into particular vocabularies in dance in a deep and committed way through collaborating with a connoisseur, avoiding generic and all-encompassing dance languages. This echoes how (Ciolfi Felice et al. 2018) argues that designers should honor the diversity of each style and choreographic approach in dance, as they are an endless source of knowledge that can be generative to the design of technologies and particularly those targeting embodied, somatic, and kinesthetic activities (Ciolfi Felice et al. 2018; Zhou et al. 2021). Having Elisabeth involved in every step of the design process led us to design a system that has been tailored to the philosophy of Isadora Duncan. Our systems are not meant to accommodate other dance approaches. Our design is centered on Duncan's style and favors depth of knowledge and specificity over generalizability.

Throughout the process, we moved away from most teaching methods which focus on dissecting the learner's movement in order to correct them using different ways to analyse motion Raheb et al. 2019. We focused on the embodied feeling of the Duncanian movement, remaining faithful to Duncan's philosophy of learning movement "*Such movements will always have to depend on and correspond to the form that is moving*" (Duncan 1928)

9.1.2 Building Bridges between HCI, Computer Graphics and Dance

Coming from a computer graphics background, trying to design systems that would meet the requirements for both the HCI world and the computer graphics world was extremely cumbersome, especially when using a co-design methodology. Indeed, during a typical computer graphics design process, the developer tends to wait until the final version to show it to the user. On the opposite side, a user centered design process, such as a co-design process includes frequent feedback throughout the process. Moreover, as a computer scientist, I used to look mainly for numerical data such as metrics in order to validate a system, overlooking the user's experience. Indeed it happened more than once that I was

focused on technicalities that on the other hand the users don't even notice. On the other hand, it is sometimes frustrating to design systems that would technically take too much time to be able to have user's feedback. I argue that both communities need to create more collaborations as to create better designs that are both efficient in the terms of technical metrics, but also useful for users. As a researcher and a dancer, trained in ballet for 20 years, I used both knowledge to communicate with Elisabeth in order to "translate" dance language into computer science and vice versa. This co-design process not only enabled me to design new prototypes, but made me better in my dance practice. Trying to dance as much as possible made the design better because it put me in the position of a user, and made me understand the kinesthetic challenges of the designs. I value design practices that dig even deeper in the somatic design, such as the work of (Bang et al. 2023) which can even be described as "slow design".

9.2 Motion Retargeting

The motion retargeting problem, which consists of transferring the animation of one animated skeleton to another with different morphology, can be compared to the teacher-student relationship in a dance class. The initial animated skeleton is the teacher/choreographer, and the student tries to transfer the dance motion to his body while considering its specificities. This parallel could bring new ideas to generate systems for motion retargeting by observing how students learn new movements and "translating" them into technical algorithms. Conversely, those retargeting methods can bring new ideas for the designer to create systems that support dance transmission.

As explained in Chapter 8, evaluating how realistic a new animation is on a skeleton is cumbersome. Indeed, the realisticness of a motion is subjective and can be hard to put into a metric. Moreover, when looking at dance motion, especially Isadora Duncan's motion, fluidity is a central aspect of her movement. However, just like the realisticness of a motion, fluidity can be hard to define as it can be seen as subjective. In a recent study, (Piana et al. 2016) defines a metric to quantify the fluidity of a motion. This work could be used as a new metric to evaluate retargeted motions, quantifying how the motion's fluidity remains throughout the retargeting process.

9.3 Looking at the Feet

The lack of feet representation has been a central concern throughout this PhD work. When reflecting on the motion capture session with Elisabeth, she explained that the shoes she



had to wear to track her movements restrained her in her movements, as she is used to performing Duncan's choreography barefoot. Later in the design process of the ribbons, the feet' articulation markers were not taken into account so as not to generate undesired bending of the end of the leg ribbons (Section 4.9). This lack of feet representation in the ribbon model made the participant feel like the ribbon model was floating in space and, therefore, lacked information about grounding (Section 5.2.5.2 and 7.2.1.1). Lastly, there was some artifact around the feet on the output animated skeleton of our motion retargeting system due to the lack of ankle and foot information.

In dance, the feet play a central role because they are related to how the dancer will be grounded, which influences the quality of the dance. Grounding is essential because it defines the relationship to the floor and how the dancer uses it to produce new movements. For instance, in classical ballet technique, the ground is used to lift the dancer upwards, pulling the center of gravity up, leading to the dancer looking like they are floating in the air. Conversely, some other dance styles, such as Dancehall or hip-hop, are considered more grounded, where the dancer gives into the ground, lowering their center of gravity for stability. Therefore, having a faithful feet representation is crucial to help students understand the grounding of the dance style. Most Dance Interactive Learning Systems (IDL) rely on motion capture to record either the teacher's or the student's movement (Raheb et al. 2019). However, motion-captured data is usually transformed into skeletal data (whether it is a skeleton with an added skin or not). In classical skeletal animation, a foot is represented as a set of two bones with one articulation (representing all the toe's Metatarsophalangeal joints). The feet' joints are not even considered and represented in some settings. However, in dance, the articulation of the feet is essential, and the foot's anatomy is more complex than just one joint. While biomechanical systems have been aimed toward dance movement to represent the foot (Veirs et al. 2022), those models are not widespread in motion capture systems and, therefore, not used in existing systems that aim to represent and teach dance. Future work could involve creating a more precise representation of the feet, helping students learn about the relationship to the ground. Moreover, systems could be developed focused on teaching such an aspect of dance without relying on accurately depicting the foot's articulation. In their work (Senecal et al. 2020), where they teach students how to salsa dance in VR, they lead the students to learn about foot placement by displaying the aimed position of the feet on the ground. However, more information could be given to the student, such as the way to step on the grounds (for instance, in salsa dancing, a step is performed with the ball of the foot first, and in some specific styles, the heel should not touch the ground at all).

9.4 Looking at Different Audiences

Throughout this PhD thesis, I conducted evaluations of our systems with a group of mostly highly experienced dancers. The insights gathered from this group proved invaluable due to their profound expertise within the domain. However, it is essential to acknowledge that these highly experienced dancers exhibited deeply ingrained habits, which might have influenced their interactions with the systems, which led to a lot of friction with the Augmented Reality headset. Indeed, it is well documented that dance is of the artistic domain in which artists accept and use less technologies in their day to day practices, especially dance styles which are taught in conservatories such as ballet and contemporary dance (Trajkova et al. 2021). On the other hand, highly trained dancers have an excellent knowledge of their body and how to move it in space. To enrich our perspective and gain a more comprehensive understanding of the potential implications of our work, it is imperative to consider a broader spectrum of users, including novices who essentially represent a blank canvas in terms of dance technology adoption.

Furthermore, during a presentation of the ribbon model in the Hololens headset to middle schoolers in the context of a field trip day to showcase younger students what computer science researchers can do, I introduced the students to the Hololens headset displaying the animated ribbons. Students were able to interact with our prototypes freely, without prior training with the headset. Notably, I observed a surprising phenomenon, as these children rapidly engaged with the prototypes, some even dancing with the prototypes, even within the confines of a bustling school hallway, without ever expressing any form of friction with the technology. While this observation should be interpreted cautiously, as it was not part of a recorded experiment, it introduces a thought-provoking discourse concerning the impact of user demographics on technology adoption and interaction patterns.

A possible explanation of this phenomenon is the generational disparity in technology familiarity and utilization. It is well-documented that younger generations exhibit a higher degree of familiarity with emerging technologies, such as augmented and virtual reality (AR/VR), in comparison to their older counterparts (Westerman et al. 2000). Moreover, younger children exhibit faster learning abilities and higher adaptability when confronted with novel experiences, facilitating accelerated proficiency acquisition of new technological skills.

In future work I would like to study how dance knowledge and generational differences can affect the perception and interaction with the systems that we developed, and how we can develop systems that take into consideration those differences.

9.5 Environmental and Societal Impact

In the context of an increasingly prominent global concern regarding the implications of climate change for our society, it is important that the environmental impact of our research are integrated into the design process of new prototypes. Evidencing the urgency of this matter, the recent publication of the Intergovernmental Panel on Climate Change (IPCC) report (Climate Change (IPCC) 2023) has unequivocally underscored the pressing need for immediate action to mitigate climate change impacts (IPCC, 2023), pressing for drastic reduction of greenhouse gas to keep global warming under 1.5°C.

In the specific context of this thesis, I want to address a critical facet of this challenge: the environmental impact of emerging technologies, such as Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (XR), with a particular focus on the use of augmented reality headsets. It is worth noting that the extant literature on the environmental impact of AR, VR, and XR technologies is quasi non existant. In their roundtable on the environmental impact of the metaverse, Souchet found only one article highlighting that environmental impact of a VR headset (Souchet 2022). This scarcity of research presents a significant knowledge gap, given the rapidly evolving landscape of immersive technologies and their potential consequences for the environment. Beyond the commonly examined metric of carbon footprint, it also is crucial to broaden our considerations to encompass additional ecological concerns, such as plastic waste generation and resource-intensive mining processes.

While I do not advocate for the large-scale adoption of my designed prototypes and there of such new technologies, my work still uses and advertised the benefits of AR. I therefore advocate for increased research efforts within the field to equip researchers and designers with comprehensive insights into the potential ramifications of their innovations. This understanding will enable more informed decisions regarding technology deployment and inspire sustainable design practices.

Furthermore, beyond the environmental impact of AR and VR, there is increasing research in the potential health impacts of these technologies on users. As demonstrated in a recent study (Souchet et al. 2022), the negative effects Virtual Reality can have on eyesight is concerning. This aspect underscores the necessity of a holistic examination of technology adoption, encompassing not only environmental but also physiological considerations.

Part IV

Résumé long en Français

Résumé Long en Français

Lors de la Convention de 2003 pour la Sauvegarde du Patrimoine Culturel Immatériel organisée par l'UNESCO, le Patrimoine Culturel Immatériel (PCI) a été défini comme *“les pratiques, représentations, expressions, connaissances, compétences - ainsi que les instruments, objets, artefacts et espaces culturels qui y sont associés - que les communautés, les groupes et, dans certains cas, les individus reconnaissent comme faisant partie de leur patrimoine culturel”* (UNESCO 2003). Les pratiques de danse, en tant que partie intégrante des arts du spectacle, constituent une part significative du PCI. De manière similaire à d'autres pratiques du PCI, la danse a historiquement reposé sur la transmission de ses traditions par voie orale et kinesthésique. En raison de la manière fragile dont les Patrimoines Culturels Immatériels sont transmis, l'UNESCO préconise en faveur de la recherche académique dont le but est de soutenir la sauvegarde du PCI (UNESCO 2003).

L'avènement de nouvelles technologies, telles que la vidéographie et, plus récemment, la capture de mouvement, a offert de nouvelles opportunités pour préserver et transmettre les pratiques de danse car elles permettent une capture durable du mouvement exécuté. Ces nouvelles technologies réunissent les domaines de la danse, de l'interaction homme-machine et de la graphique informatique pour ouvrir de nouvelles perspectives de sauvegarde des connaissances inestimables intégrées dans les traditions de danse, couvrant diverses cultures et styles tels que les danses folkloriques grecques et chypriotes (Aristidou et al. 2021), la danse classique indienne (Mallik et al. 2011), la danse Kasidawen chinoise (Papangelis et al. 2016). Un style de danse qui s'aligne étroitement avec les principes de préservation du Patrimoine Culturel Immatériel (PCI) est celui d'Isadora Duncan.

10.1 L'Archive Vivante d'Isadora Duncan

Isadora Duncan (1877-1927) est considérée comme l'une des fondatrices de la danse moderne et contemporaine. Dans son travail chorégraphique, Duncan voulait s'éloigner de la technique rigide imposée par le ballet pour retrouver ce qu'elle décrivait comme *“le mouvement naturel”*. Dans sa définition, le mouvement naturel est décrit comme non restreint, respectant à la fois la structure du corps et la gravité : *“Ces mouvements devront tou-*

jours dépendre de et correspondre à la forme qui se déplace” (Duncan 1928). Autrement dit, chaque mouvement qu’un danseur exécute est vu à travers le prisme du corps de ce danseur. Dans cette même philosophie de trouver le ”mouvement naturel”, elle a également exprimé que le centre du mouvement et de l’énergie est le plexus solaire. Ainsi, tout mouvement dans sa chorégraphie provient du plexus solaire, qui est un point anatomique situé sur le torse entre le diaphragme et le sternum.

Isadora Duncan a toujours refusé d’être filmée car elle pensait que le taux de trame de la caméra de l’époque (environ 24 images par seconde) n’était pas suffisant pour représenter la fluidité de sa chorégraphie. Ainsi, la chorégraphie a principalement été transmise de manière orale et kinesthésique d’une génération à l’autre. Bien qu’une partie de son répertoire ait été traduite en notation de danse (comme la notation Laban et la notation Sutton) comme moyen de tenter d’archiver et de sauvegarder ses connaissances chorégraphiques, ces notations sont difficiles à déchiffrer et peu connues dans la communauté de la danse. De plus, elles ne transcrivent pas la philosophie du mouvement du chorégraphe. De nos jours, seulement très peu de danseurs sont experts dans le répertoire d’Isadora Duncan, et il n’est plus transmis dans le programme de danse régulier. On peut même aller jusqu’à considérer qu’il est en voie d’extinction.

Le projet Isadora Living Archive a été créé pour répondre aux préoccupations de sauvegarde du répertoire d’Isadora Duncan et garantir sa préservation. Ce projet est une collaboration entre mes superviseurs Sarah Fdili Alaoui (Inria Paris Saclay, équipe Ex-Situ), Rémi Ronfard et Mélina Skouras (Inria Grenoble, équipe ANIMA), le MocapLab, le Centre National de la Danse, l’experte en danse Isadora Duncan, Elisabeth Schwartz, et moi-même (Laboratoire Jean Kuntzmann Grenoble). En tant que première étape de ce projet, nous avons enregistré avec le MocapLab un ensemble de pièces de danse d’Isadora Duncan interprétées par Elisabeth en utilisant la technologie de capture de mouvement. Ensuite, en utilisant ces données capturées par mouvement, nous avons cherché à créer des outils qui aident à sauvegarder la danse d’Isadora Duncan et à transmettre ses qualités de mouvement à un large public.

10.2 Questions de Recherche

Dans le cadre du projet Isadora Duncan Living Archive et de ma thèse de doctorat, j’ai porté mon attention sur le thème de la *transmission de la danse*. En effet, comme décrit dans la section précédente, la philosophie d’enseignement et de transmission de la danse de Duncan réside dans le fait que le danseur comprenne sa philosophie du mouvement pour faire sien le mouvement et ressentir les qualités de sa danse dans son corps, plutôt que de simplement imiter ce qu’il voit et le reproduire. En essence, l’objectif n’est pas de *imiter*

mais d'*incarner*.

Une manière de sauvegarder son travail tout en suivant sa philosophie est donc de se concentrer sur la transmission de ses qualités de danse et non pas simplement de créer une collection d'enregistrements vidéo de ses élèves interprétant ses pièces de danse. C'est pourquoi, dans cette thèse, j'ai concentré mes efforts sur la conception de systèmes qui transmettent les qualités de la danse.

Plus précisément, je me suis d'abord concentré sur la transmission de qualités spécifiques du style de danse de Duncan : le plexus solaire, la vague et la fluidité. J'ai posé la question de recherche suivante :

Comment les qualités de mouvement d'Isadora Duncan peuvent-elles être représentées ?

Pour répondre à cette question, j'ai suivi, avec mes superviseurs, un processus de co-conception sur trois ans avec notre collaboratrice et experte dans le style d'Isadora Duncan, Elisabeth Schwartz. En tant que danseuse ayant été formée au ballet pendant plus de 20 ans et ayant récemment ouvert sa formation à de nouveaux styles de danse tels que le contemporain, la danse urbaine et la salsa, j'ai utilisé mes connaissances en danse pour communiquer avec Elisabeth et créer des designs que j'aimerais utiliser dans le studio de danse. D'autre part, en tant qu'informaticien, j'ai utilisé mes compétences en graphisme informatique et en interaction homme-machine pour implémenter et évaluer les artefacts conçus.

Au cours de la première phase de ce processus de co-conception, nous avons créé une visualisation abstraite d'un corps dansant composé de 5 rubans flexibles reliés ensemble au niveau du plexus solaire. Nous avons inclus ce modèle 3D dans un casque de réalité augmentée afin que les utilisateurs puissent voir le modèle danser dans l'espace. Nous avons ensuite évalué le modèle avec des danseurs. Les commentaires des danseurs ont donné naissance à la deuxième question de recherche :

Comment la perception de l'espace peut-elle être améliorée dans la danse en utilisant la réalité augmentée ?

Pour répondre à cette question, j'ai continué le processus de co-conception avec Elisabeth. Nous nous sommes inspirés d'une notation de danse appelée Sutton pour créer un système qui visualise nos modèles de rubans, des "keyframes" animés et la trajectoire que le plexus solaire laisse dans l'espace.

Enfin, nous nous sommes inspirés du modèle de ruban et de la *ligne d'action* représentée dans Guay et al. 2013 pour créer un troisième système. La ligne d'action est une ligne 2D dessinée par les dessinateurs de bandes dessinées pour les aider à poser des personnages.

Dans leur travail, Guay et al. 2013 ont créé un système qui pose un squelette 3D (utilisé pour animer les personnages) à partir d'une ligne d'action dessinée, imitant le travail du dessinateur de bandes dessinées. Nous avons comparé notre ruban généré à la ligne d'action et pensé que les rubans pourraient poser un autre squelette en utilisant un processus similaire. Si cette opération est réalisée sur l'ensemble des rubans d'une danse d'Isadora Duncan, cela animerait le personnage résultant. La dernière question de recherche est donc :

Comment le modèle de ruban peut-il être utilisé pour transférer une animation de danse d'un personnage animé à un autre ?

Pour répondre à cette question, nous avons créé un système basé sur l'optimisation qui anime un squelette à partir de notre ruban animé en utilisant une énergie de ressort. Nous avons été en mesure de transférer l'animation à des squelettes humanoïdes avec différents nombres d'os et de longueurs d'os.

10.3 Contributions

Les contributions de cette thèse sont énumérées ci-dessous :

10.3.1 Contributions de Conception

Au cours du processus de co-conception, les contributions suivantes ont été réalisées :

- La conception d'une nouvelle représentation abstraite 3D d'un corps dansant. Ce modèle est composé de cinq rubans flexibles reliés ensemble au niveau du plexus solaire pour représenter un corps dansant et est animé à partir de données capturées par mouvement.
- La conception d'un système qui visualise les rubans animés, ainsi que des keyframes animés que nous avons appelés moments d'impulsion et la trajectoire du plexus solaire, pour améliorer la visualisation de l'espace dans le casque de réalité augmentée Hololens 2.
- La compréhension approfondie de la philosophie du mouvement d'Isadora Duncan à travers notre processus de co-conception de trois ans avec une danseuse experte dans le style d'Isadora Duncan.

10.3.2 Contributions Expérimentales

Tout au long de notre évaluation avec des danseurs, nous avons apporté les contributions suivantes :

- L'évaluation avec des danseurs lors de deux ateliers de notre modèle de ruban en forme d'étoile. Les résultats montrent que cette représentation abstraite transmet fidèlement les qualités de mouvement d'Isadora Duncan.
- L'observation structurée de notre système qui soutient la perception de l'espace avec des danseurs. Nos résultats suggèrent qu'il n'existe pas un seul système qui convient à tous les besoins, mais plutôt une variété de systèmes pour différents usages, de l'observation à la danse, en passant par l'improvisation avec le système.

10.3.3 Contributions en Animation Informatique

Les contributions de cette thèse en animation informatique sont énumérées ci-dessous :

- Une nouvelle manière d'animer des rubans à partir de données capturées par mouvement en utilisant le cadre des tiges élastiques discrètes introduit dans (Bergou et al. 2008). Les paramètres de ce cadre sont ensuite étudiés à l'aide de résultats visuels et numériques.
- Une nouvelle manière de transférer l'animation du mouvement de danse d'un personnage animé à un autre en utilisant les rubans comme lignes d'action. Les rubans sont générés à partir de l'animation de danse en entrée. Ensuite, le squelette cible est animé à l'aide d'un algorithme d'optimisation à chaque pas de temps.

10.4 Structure du Manuscrit

Ce manuscrit est structuré autour de trois parties, chacune abordant l'une des trois questions de recherche définies dans la section précédente. Cette structure est détaillée comme suit :

- **Chapitre 2** décrit les travaux précédents dans le contexte de la transmission de la danse par la visualisation d'un corps dansant, les moyens augmentés pour apprendre le mouvement, l'animation de croquis de mouvement de danse et le réadressage de mouvement.

- **Partie Un: Comment les Qualités de Mouvement d'Isadora Duncan Peuvent-Elles Être Représentées ?**
 - **Chapitre 3** décrit la collaboration avec la danseuse Elisabeth Schwartz à travers un processus de co-conception et le premier processus de conception itérative d'une visualisation abstraite de la danse d'Isadora Duncan. Le design final est un ensemble de cinq rubans flexibles reliés ensemble au niveau du plexus solaire.
 - **Chapitre 4** décrit la méthode pour animer les rubans conçus à partir de données capturées par mouvement et le choix des paramètres du modèle mathématique.
 - **Chapitre 5** décrit l'évaluation du modèle de ruban avec des danseurs professionnels lors de deux ateliers utilisant un écran 2D et un casque de réalité augmentée.
- **Partie Deux: Comment la Perception de l'Espace Peut-Elle Être Améliorée dans la Danse en Utilisant la Réalité Augmentée ?**
 - **Chapitre 6** s'appuie sur les résultats du chapitre 5 pour améliorer le modèle affiché en réalité augmentée afin de soutenir la perception de l'espace. Le nouveau système a été créé en observant un processus de co-conception avec notre danseuse experte, Elisabeth Schwartz.
 - **Chapitre 7** décrit l'observation structurée (Garcia et al. 2014) de trois variations de ce système mentionné précédemment lors d'un atelier avec des danseurs.
- **Partie Trois: Comment le Modèle de Ruban Peut-Il Être Utilisé pour Transférer une Animation de Danse d'un Personnage Animé à un Autre ?**
 - **Chapitre 8** décrit une nouvelle manière d'utiliser les rubans générés dans le chapitre 4 pour transmettre le mouvement de danse d'un squelette animé à un autre. Ce chapitre décrit un travail en cours.
- **Chapitre 9** discute des résultats de la thèse et des opportunités possibles d'élargissement dans les travaux futurs.

10.5 Publications

Les contributions des chapitres 3, 4 et 5 ont conduit à la publication examinée par des pairs suivante lors de la conférence Creativity and Cognition :

Manon Vialle, Sarah Fdili Alaoui, Mélina Skouras, Vennila Vilvanathan, Elisabeth Schwartz, and Remi Ronfard (2022). “Visualizing Isadora Duncan’s Movements Qualities”. In: *Creativity and Cognition*. C&C ’22. Venice, Italy: Association for Computing Machinery, pp. 196–207

La contribution des chapitres 6 et 7 a conduit à la publication examinée par des pairs suivante lors de la conférence Creativity and Cognition :

Manon Vialle, Sarah Fdili Alaoui, Mélina Skouras, and Elisabeth Schwartz (2023). “Supporting Perception of Spatiality in Dance in Augmented Reality”. In: *Proceedings of the 15th Conference on Creativity and Cognition*. C&C ’23. Virtual Event, USA: Association for Computing Machinery, pp. 441–453

Mathematical notations

A.1 Vector Operations

Let $n \in \mathbb{N}$, $\mathbf{a} \in \mathbb{R}^n$ and $\mathbf{b} \in \mathbb{R}^n$ we use the following notations:

- Dot product: $\mathbf{a} \cdot \mathbf{b} = \sum_{k=1}^n a_k b_k \in \mathbb{R}$
- Cross product: $\mathbf{a} \times \mathbf{b} = \left(\sum_{i=1}^3 \sum_{j=1}^3 \mathcal{E}_{kij} a_i b_j \right)_{k \in \llbracket 1,3 \rrbracket} \in \mathbb{R}^3$ (where \mathcal{E} is the Levi-Civita symbol)
- Elementwise sum: $\mathbf{a} + \mathbf{b} = (a_k + b_k)_{k \in \llbracket 1,n \rrbracket} \in \mathbb{R}^n$
- Elementwise subtraction: $\mathbf{a} - \mathbf{b} = (a_k - b_k)_{k \in \llbracket 1,n \rrbracket} \in \mathbb{R}^n$
- Norm: $\|\mathbf{a}\| = \sqrt{\mathbf{a} \cdot \mathbf{a}} = \sqrt{\sum_{k=1}^n (a_k)^2} \in \mathbb{R}$
- Angle between two vector: $\widehat{ab} = \arctan \frac{\|\mathbf{a} \times \mathbf{b}\|}{\mathbf{a} \cdot \mathbf{b}}$

A.2 Principal Component Analysis

Principal component analysis has been introduced F.R.S. 1901. In this part I will explain how I used PCA in the case of the generation of the initial ribbon. Let $(s_k)_{k \in [0,n]}$ be a set of $n + 1$ 3D markers (that is in \mathbb{R}^3). Let M be the matrix such that

$$M = \begin{pmatrix} s_{x_0} & s_{y_0} & s_{z_0} \\ \vdots & \vdots & \vdots \\ s_{x_n} & s_{y_n} & s_{z_n} \end{pmatrix} \quad (\text{A.1})$$

Let us denote \bar{M} the centered matrix, such that

$$\bar{M} = M - \begin{pmatrix} \bar{s}_x & \bar{s}_y & \bar{s}_z \\ \vdots & \vdots & \vdots \\ \bar{s}_x & \bar{s}_y & \bar{s}_z \end{pmatrix} \quad (\text{A.2})$$

where

$$\begin{pmatrix} \bar{s}_x \\ \bar{s}_y \\ \bar{s}_z \end{pmatrix} = \frac{1}{n+1} \begin{pmatrix} \sum_{i=0}^n s_{x_i} \\ \sum_{i=0}^n s_{y_i} \\ \sum_{i=0}^n s_{z_i} \end{pmatrix} \quad (\text{A.3})$$

is the center of gravity of the set of markers. Performing a principal component analysis is then finding the eigenvalues and corresponding eigenvectors of the following matrix :

$$\frac{1}{n+1} \bar{M}^T \bar{M} \quad (\text{A.4})$$

In this case we end up with 3 eigenvalues λ_0 , λ_1 and λ_2 and corresponding eigenvectors v_0 , v_1 and v_2 . We number them such that $|\lambda_0| \geq |\lambda_1| \geq |\lambda_2|$.

A.3 Spring Energy

Hooke's law give the force F_{spring} of a spring of position at rest \bar{x} and current position a :

$$F_{spring} = -a\Delta x$$

where $\Delta x = \bar{x} - x$ and a is the rigidity of the spring. The energy E_{spring} of the spring is then

$$E_{spring} = - \int F_{spring} \cdot dx = - \int -ax \cdot dx = \frac{1}{2}ax^2 = \frac{1}{2}a(\bar{x} - x)^2.$$

A.4 Hausdorff Distance

First let us define the distance between a point p and a set S as the minimal euclidian distance between p and the points in S : $d(p, S) = \min_{q \in S} \|p - q\|$. We then define the distance between a set S_a and another set S_b by $d_{set}(S_a, S_b) = \sup_{p_a \in S_a} d(p_a, S_b)$. Note that this distance is not symmetrical, which means $d_{set}(S_a, S_b) \neq d_{set}(S_b, S_a)$. Therefore we define the Hausdorff as the maximum between the two :

$$d_{\text{Hausdorff}}(S_a, S_b) = \max(d_{set}(S_a, S_b), d_{set}(S_b, S_a)).$$

A.5 Weight Ratio

Let β_1, β_2 and q_{1_k}, q_{2_k} such that $\beta_1 \neq \beta_2, q_{1_k} \neq q_{2_k}$ and $\frac{\beta_1}{q_{1_k}} = \frac{\beta_2}{q_{2_k}}$. Let us prove that:

$$\operatorname{argmin}(\beta_1 E_{\text{twist}}(\Gamma) + q_{1_k} E_{\text{angular}}(\Gamma)) = \operatorname{argmin}(\beta_2 E_{\text{twist}}(\Gamma) + q_{2_k} E_{\text{angular}}(\Gamma)) \quad (\text{A.5})$$

Let $A \subset \mathbb{R}^n, f : A \rightarrow \mathbb{R}$. Let us define $x^* \in A$ such that $x^* = \operatorname{argmin}_{x \in A} f(x)$. Then we have

$$\forall \alpha > 0, x^* = \operatorname{argmin}_{x \in A} \alpha f(x).$$

Let $\alpha \in \mathbb{R}$ such that $\alpha > 0$.

$$\begin{aligned} x^* = \operatorname{argmin}_{x \in A} f(x) &\iff \forall x \in A, f(x^*) \leq f(x) \\ &\iff \forall x \in A, \alpha f(x^*) \leq \alpha f(x) \\ &\iff x^* = \operatorname{argmin}_{x \in A} \alpha f(x) \end{aligned}$$

Let's denote $E_1(\Gamma) = \beta_1 E_{\text{twist}}(\Gamma) + q_{1_k} E_{\text{angular}}(\Gamma)$ and $E_2 = \beta_2 E_{\text{twist}}(\Gamma) + q_{2_k} E_{\text{angular}}(\Gamma)$. Then

$$\begin{aligned} \frac{\beta_2}{\beta_1} E_1(\Gamma) &= \frac{\beta_2}{\beta_1} (\beta_1 E_{\text{twist}}(\Gamma) + q_{1_k} E_{\text{angular}}(\Gamma)) \\ &= \beta_2 E_{\text{twist}}(\Gamma) + q_{1_k} \frac{\beta_2}{\beta_1} E_{\text{angular}}(\Gamma) \\ &= \beta_2 E_{\text{twist}}(\Gamma) + q_2 E_{\text{angular}}(\Gamma) \quad \text{since } \frac{\beta_1}{q_{1_k}} = \frac{\beta_2}{q_{2_k}} \Leftrightarrow q_2 = \frac{q_{1_k} \beta_2}{\beta_1} \\ &= E_2(\Gamma). \end{aligned}$$

Therefore

$$\operatorname{argmin}(\beta_1 E_{\text{twist}}(\Gamma) + q_{1_k} E_{\text{angular}}(\Gamma)) = \operatorname{argmin}(\beta_2 E_{\text{twist}}(\Gamma) + q_{2_k} E_{\text{angular}}(\Gamma)). \quad (\text{A.6})$$

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Conception et Évaluation de Systèmes 3D pour la Transmission de Mouvement Dansé

Résumé — Dans cette thèse, mon objectif est de concevoir et d'évaluer des systèmes 3D pour la transmission du mouvement en danse. J'explore la transmission de la danse à travers deux dimensions : la transmission de certains aspects spécifiques d'un style de danse aux danseurs, et la transmission d'une animation de danse d'un personnage virtuel animé à un autre. Lors de la transmission d'aspects spécifiques d'un style de danse aux danseurs, j'ai collaboré avec une danseuse experte dans le style d'Isadora Duncan pour créer des systèmes 3D en réalité augmentée. Une première contribution réside dans la co-conception, la mise en œuvre technique et l'évaluation avec les danseurs d'un artefact virtuel qui transmet la fluidité du mouvement. Ce système permet de visualiser des rubans en forme d'étoile joints au plexus solaire, animés à partir de données de capture de mouvement des danses d'Isadora Duncan. L'animation est créée via un algorithme d'optimisation. L'évaluation s'est déroulée sous la forme d'ateliers et a montré un grand potentiel du système pour transmettre les qualités du mouvement d'Isadora Duncan qu'une représentation de type humain ou basée sur un squelette échoue à transmettre. Sur la base des retours de la première contribution, j'ai co-conçu avec la même danseuse experte un second système qui vise à aider la perception de la spatialisation de la danse en réalité augmentée. Cette deuxième contribution réside dans la conception et l'évaluation du système. Avec la danseuse experte, nous nous sommes inspirées de la notation Sutton pour créer un système qui visualise des poses clés animées à partir de la danse et la trace du plexus solaire dans l'espace. J'ai ensuite mené une observation structurée pour évaluer les différences dans le nombre d'images clés affichées en même temps. Mes résultats montrent le potentiel de la réalité augmentée à des fins pédagogiques. La dernière contribution de cette thèse réside dans le deuxième aspect de la transmission de la danse : la transmission de la danse animée d'un personnage virtuel à un autre. J'ai créé un système qui prend en entrée des données de capture de mouvement d'une danse et les transfère à un autre corps qui peut avoir une morphologie différente. Pour ce faire, je génère d'abord des rubans à partir des données de capture de mouvement (squelette animé ou ensemble de marqueurs). Ensuite, j'associe chaque ruban à une chaîne articulée du squelette cible. Enfin, j'applique l'animation contenue dans les rubans sur le squelette cible à l'aide d'un algorithme d'optimisation.

Mots clés : réalité augmentée, animation par ordinateur, danse, visualisation de mouvement, rubans, IHM

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Design and Evaluation of 3D Systems for Movement Transmission in Dance

Abstract — In this thesis, I aim to design and evaluate 3D systems for movement transmission in dance. I explore dance transmission through two dimensions: transmission of specific aspects of a dance style to dancers and transmission of the animated dance from one virtual animated character to another. When transmitting specific aspects of a dance style to dancers, I collaborated with a connoisseur dancer in Isadora Duncan’s style to create 3D systems in augmented reality. A first contribution is the co-design, technical implementation, and evaluation with dancers of an artifact that transmits the fluidity of movement. This system visualizes star-shaped ribbons joined at the solar plexus animated from motion-captured data of Isadora Duncan’s dances. The animation is performed using an optimization-based algorithm. The evaluation took place as a series of workshops. It showed great potential for the system to transmit the qualities of Isadora Duncan’s movement that a human-like or skeleton-based representation fails to transmit. Based on the feedback of the first contribution, I co-designed with the same connoisseur dancer another system that supports the perception of spatiality in dance in augmented reality. This second contribution lies in the design and evaluation of the system. Along with the expert dancer, I took inspiration from the Sutton notation to create a system that visualizes animated keyframes of the dance and the trace of the solar plexus in space. I then ran a structured observation to evaluate the differences in the number of keyframes displayed simultaneously. My results show the potential of augmented reality for pedagogical purposes. The last contribution of this thesis lies in the second aspect of dance transmission: transmission of the animated dance from one virtual animated character to another. I created a system that takes as an input motion-captured data of a dance and transfers it to another body with a different morphology. To achieve this, I first generate ribbons from the motion-captured data (animated rig or set of markers). Then, I match each ribbon with an articulated chain of the target rig. Lastly, I apply the animation contained in the ribbons onto the target rig using an optimization algorithm.

Keywords: augmented reality, computer animation, dance, movement visualisation, ribbons, HCI

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