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Les effets aigus du port de vêtements de compression sur le contrôle postural

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COMPOSANTE STAPS

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Présentée et soutenue par **Kévin Baige**

Le 28 juin 2022

**Les effets aigus du port de vêtements de compression sur le
contrôle postural**

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A Eméo...

Dans la vie, rien n'est à craindre, tout est à comprendre.

Marie Curie (1867-1934)

C'qui compte c'est pas l'arrivée, c'est la quête.

Orelsan (Civilisation, 2021)

You will never know what you're capable of unless you try.

unknown author

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Liste des abréviations :

AP : antéro-postérieur

APA : ajustements posturaux anticipateurs

APC : ajustements posturaux consécutifs

APS : ajustements posturaux simultanés

AVC : accident vasculaire cérébral

CG : compression garments / vêtements de compression

CM : centre de masse

CP : centre des pressions

DDL : degrés de liberté

FA : fast adaptations / adaptations rapides

FNM : fuseaux neuromusculaires

KT : kinesiotaping / bande de kinésiologie

LCA : ligament croisé antérieur

ML : médio-latéral

OTG : organes tendineux de Golgi

RS : résonance stochastique

S : surface

SA : slow adaptations / adaptations lentes

SNC : système nerveux central

UM : unité motrice

Introduction

L'utilisation de vêtements de compression connaît un fort accroissement dans le monde sportif depuis ces dernières années. Tout d'abord utilisés en médecine pour favoriser les flux hémodynamiques des patients ou pour éviter les thromboses post opératoires (Lattimer et al., 2013), les vêtements compressifs ont, par la suite, été détournés de leur usage pour améliorer les performances sportives. En effet, ces dispositifs créent un gradient de pression à la surface du corps qui améliore le retour veineux, la circulation sanguine et, par voie de conséquence, l'oxygénation musculaire (Dermont et al., 2015; Hill et al., 2014; Lattimer et al., 2013). Cela explique en partie pourquoi cette aide ergogénique (compression) améliore la récupération post exercice (Brown et al., 2017; Hill et al., 2014; Ménétrier et al., 2013), certaines qualités physiques (Born et al., 2013; Engel et al., 2016) et permet de lutter contre les facteurs de stress physiologiques des sportifs en déplacement lors des vols longs courriers (Broatch et al., 2019; Kraemer et al., 2010). Par ailleurs, You et al., (2004) ont rapporté que l'application d'un dispositif compressif au niveau de l'articulation de la cheville permettait d'améliorer l'acuité proprioceptive des sujets. Etant donné les effets bénéfiques que peuvent avoir des dispositifs compressifs sur l'acuité proprioceptive de certains individus (Barss et al., 2018; Woo et al., 2021; You et al., 2004), ceux-ci pourraient favoriser la précision des mouvements segmentaires régulateurs du contrôle postural.

Le contrôle postural a pour fonction de préserver l'équilibre général du corps en fonction des contraintes spatiales et environnementales par l'implication de mécanismes finement élaborés et propres à chaque individu. Il assure ainsi la double fonction, d'orientation et de stabilisation du corps dans l'espace (Massion, 1994). Certaines études se sont interrogées sur l'impact que pourraient avoir les vêtements de compression sur le contrôle postural au regard des effets constatés sur la proprioception (Barss et al., 2018; Woo et al., 2021; You et al., 2004). Outre l'effet mécanique induit par l'application de ces dispositifs tactiles, ces derniers faciliteraient l'exploitation du "bruit du système sensorimoteur" par le système nerveux central (Woo et al., 2014). Il s'agit d'un phénomène de résonance stochastique qui peut induire des effets bénéfiques sur le contrôle postural (Davids, 2004). A notre connaissance peu d'études ont analysés les effets aigus des vêtements de compression sur le contrôle postural (Cavanaugh et al., 2016; Hijmans et al., 2009; Kuster et al., 1999; Michael et al., 2014; Palm et al., 2012; Sperlich et al., 2013; Woo et al., 2018, 2014). Au regard de la littérature, aucun consensus n'a pu être dégagé, sans doute à cause de la disparité des sujets recrutés et de la diversité des types

de vêtements de compression utilisés (Reich-Schupke et al., 2016; Woo et al., 2018). Ainsi, les effets aigus du port de vêtements de compression sur le contrôle postural sont encore discutés.

Lors de ce travail de thèse nous tâcherons d'identifier les effets aigus de la stimulation tactile sur le contrôle postural lors du port de manchons de compression sur le membre inférieur. Dans une première partie nous proposerons un cadre théorique lié à cette thématique et les enjeux qu'elle comporte. Dans une seconde partie, nous présenterons les trois études expérimentales pour tenter de répondre à nos problématiques préalablement posées. Enfin, dans une troisième partie nous discuterons des résultats obtenus et des écueils rencontrés et suggérerons une conclusion qui s'achèvera par des perspectives à ce travail expérimental.

Partie I : Cadre Théorique

1. Approche générale du contrôle de l'équilibre

1.1. Contraintes biomécaniques et conséquences associées

1.1.1. Equilibre et posture érigée

1.1.1.1. Identification des contraintes

Le contrôle postural est généralement défini comme la capacité à maintenir la position relative de l'ensemble des différents segments corporels à un instant donné (Massion, 1994). Il a une fonction antigravitaire et permet aussi le soutien et la préparation au mouvement. Dans ce cadre, il a une fonction d'interface avec le monde extérieur pour la perception et l'action (Massion, 1994).

La conservation d'une posture orthostatique est dépendante d'un contrôle postural efficient. En condition d'appui bipodale, la zone entre les deux pieds ainsi que la surface de chaque pied constituent ce que l'on nomme le polygone de sustentation. En condition d'appui unipodale, le polygone de sustentation correspond à la surface sous le pied d'appui. Ainsi, maintenir le corps en équilibre consiste à agencer les différents segments corporels de façon à ce que la verticale du centre de masse (CM) se projette à l'intérieur du polygone de sustentation (Figure 1).

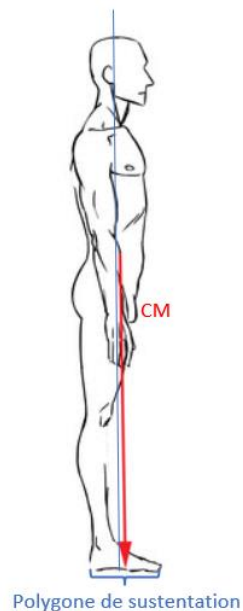


Figure 1 : Illustration de la verticale orthogonale; d'après (Bouisset & Maton, 1996)

D'un point de vue biomécanique, l'équilibre est une notion précise, qui renvoie au principe fondamental de la statique. Un corps est en équilibre, dans un référentiel galiléen, si la résultante des forces extérieures (\vec{F}_{ext}) est nulle et si le moment résultant de ces forces extérieures (\vec{M}_{ext}) est également nul (première loi de Newton). Nous avons ainsi :

$$\begin{aligned}\sum \vec{F}_{ext} &= \vec{0} \\ \sum \vec{M}_O \vec{F}_{ext} &= \vec{0}\end{aligned}$$

Si ces conditions d'équilibre ne sont pas respectées, la loi de la dynamique fondamentale du mouvement (seconde loi de Newton) s'applique. Elle stipule que l'accélération d'un corps est directement proportionnelle à la force agissant sur ce corps et inversement proportionnelle à sa masse, soit :

$$\sum \vec{F}_{ext} = m\vec{a}$$

Cette relation s'applique également en rotation et stipule que la somme des moments des forces externes appliquées au centre de rotation du système est égale au produit de l'accélération angulaire par le moment d'inertie ($\sum \vec{M}_O \vec{F}_{ext} = I\ddot{\theta}$).

Sous l'effet de la gravité, le corps humain est maintenu en appui sur une surface de contact avec laquelle il interagit grâce au principe d'action-réaction (troisième loi de Newton) et dont l'énoncé est le suivant : lorsqu'un corps A exerce sur un corps B une action mécanique représentée par une force $\vec{F}_{A/B}$, le corps B exerce sur A une action mécanique représentée par une force $\vec{F}_{B/A}$. Ces deux forces ont la même direction, de sens contraire et une même norme, soit :

$$\vec{F}_{A/B} = -\vec{F}_{B/A}$$

Dans le champ gravitationnel terrestre, un corps en contact avec le sol est donc soumis à l'action de son poids, qui s'applique au CM de ce corps, ainsi qu'à la force de réaction du sol, qui s'applique au niveau du centre des pressions (CP). Pour un corps inerte, la position du CP est confondue avec la projection verticale du CM au sol. Un sujet humain en station debout est cependant toujours animé de micro mouvements et ne peut donc pas être strictement (d'un point de vue mécanique) considéré comme étant dans un état d'équilibre statique (Thomas & Whitney, 1959). Ces micro mouvements sont principalement liés à des perturbations intrinsèques telles que les contractions musculaires cardiaques, les mouvements respiratoires et les mouvements liquidiens (Winter, 1995). Un statokinésigramme caractérise les excursions du CP sous la forme d'un tracé enregistré par une plateforme stabilométrique. Conforto et al. (2001) ont par exemple montré lors de la systole que l'éjection du sang par le ventricule gauche dans l'aorte ascendante génère des forces détectables dans les oscillations du CP. Des perturbations similaires ont été rapportées pour les contractions du diaphragme en position

assise ou debout (Hamaoui et al., 2014). Même si le terme « équilibre statique » est parfois employé pour caractériser une tâche posturale réalisée à partir d'un support stable (Berry & McMurray, 1987; Thomas & Whitney, 1959), l'équilibre postural est un phénomène dynamique nécessitant l'intervention de forces d'origine musculaire afin d'assurer la stabilité de la posture en maintenant le CM dans la base de sustentation (Pérennou, 2012). La stabilité posturale peut aussi être considérée comme une propriété d'un comportement coordonné dans un système soumis à un ensemble de contraintes endogènes et exogènes (Zanone & Athènes, 2013). Ces contraintes impactent nécessairement l'organisation segmentaire existante. Elles peuvent être analysées par le biais de nombreux modèles.

1.1.1.2. Modèles d'analyse

Le corps humain est un système très complexe. Il est constitué d'une multitude de pièces osseuses, mobiles les unes par rapport aux autres au niveau des articulations et mobilisées par des groupes musculaires sous le contrôle du système nerveux central (Bouisset, 1991). L'étude biomécanique nécessite que le corps humain soit préalablement matérialisé sous une forme mécanique simplifiée à partir de laquelle il est possible d'appliquer les lois de la physique (Bouisset, 2002). Le modèle du pendule inversé simple, qui considère le corps humain comme un ensemble rigide oscillant autour de l'articulation de la cheville, est le modèle le plus souvent utilisé pour étudier le contrôle de l'équilibre chez l'Homme (Winter 1995 ; Créteuil 2015).

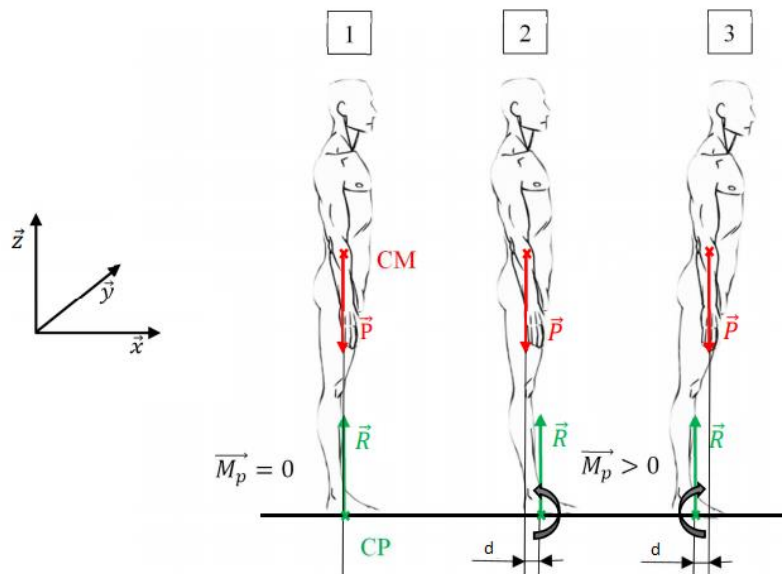


Figure 2 : *Modèle du pendule inversé simple*

\vec{P} est le poids corporel s'appliquant au CM du sujet, \vec{R} la force de réaction au sol s'appliquant au niveau du CP, d la distance entre la ligne d'action de \vec{R} et \vec{P} . \vec{M}_p , le moment induit par \vec{P} .

Le modèle du pendule inversé a notamment permis de comprendre la dynamique posturale et les interactions entre le CP et le CM (Winter, 1995). En appliquant ce modèle, le CM est considéré comme une variable « passive » dont les mouvements sont contrôlés par le CP, considéré comme une variable « active » qui rend compte des actions mises en place par le système de contrôle postural pour maintenir le corps en équilibre (Winter, 1995). La figure 2 illustre ces interactions entre le CP et le CM. Les deux forces en présence sont la force de réaction du sol (R) et le poids corporel (P). Le point d'application de la résultante des forces verticales au sol est le CP. Dans la condition numéro 1, le corps est dans un état d'équilibre transitoire. Sachant que P et R exercent une action uniquement sur l'axe vertical et que l'articulation de cheville constitue l'axe de rotation du système, les conditions d'équilibre en translation ($\sum \vec{F}_{ext} = 0$) et en rotation ($\sum \vec{M}_o \vec{F}_{ext} = 0$) sont respectées. Ainsi les forces \vec{P} et \vec{R} suivent la même direction, ont la même norme mais sont de sens opposées : elles se compensent. D'un point de vue mécanique, le pendule inversé est parfaitement équilibré dès lors que les verticales de CP et CM sont alignées. Il n'y a donc pas de moment induit par \vec{P} et $\vec{M}_p = 0$. Dans la situation numéro 2, la projection verticale du CM n'est plus alignée par rapport au CP. La relation fondamentale de la dynamique s'applique $\sum \vec{M}_o \vec{F}_{ext} = I\ddot{\theta}$. Le CM étant en arrière du CP, le poids \vec{P} induit donc un moment antihoraire par rapport à la cheville ($\vec{M}_p > 0$) qui fait osciller le corps vers l'arrière. Dans la situation numéro 3, le CM est placé en avant du CP. Le poids \vec{P} induit un moment horaire qui fait osciller le corps vers l'avant.

Plusieurs auteurs considèrent néanmoins que la posture orthostatique de l'Homme est un phénomène dynamique multi-articulaire qui ne peut être appréhendé finement par le modèle du pendule inversé simple, en particulier sur des supports instables lorsque la surface d'appui se déforme et/ou se déplace (Crétual, 2015; Günther & Wagner, 2016). Une modélisation en double ou triple pendule inversé, en intégrant l'articulation de la hanche et/ou du genou, serait plus appropriée pour appréhender finement les mécanismes impliqués dans le contrôle postural (Crétual, 2015). Günther et Wagner (2016) suggèrent en effet qu'un modèle de pendule inversé triple est plus approprié pour analyser le caractère dynamique et les propriétés structurelles essentielles de la posture humaine. Des modèles plus complexes ont été proposés en intégrant d'avantages d'articulations telles que les épaules, les coudes ou encore les espaces intervertébraux (Barton et al., 2016 ; Kilby et al., 2015). Ces modèles mettent en exergue

l'efficacité du contrôle postural dans sa capacité à coordonner différentes articulations caractérisées par une multitude de degrés de liberté.

1.1.2. Gestion des degrés de liberté articulaire

1.1.2.1. Modes de coordination et stratégies posturales

Le corps humain dispose d'un nombre important d'articulations (plus de 300) et le contrôle d'un tel nombre de degrés de liberté (DDL) articulaires, qui présentent par ailleurs une certaine redondance, peut potentiellement être problématique pour le système nerveux central (SNC) (Bernstein 1967 ; Latash et al., 2007). Bernstein (1967) a postulé que le SNC pouvait résoudre ce problème en réduisant le nombre de DDL nécessaires à la réalisation d'une tâche. Un tel « gel » des degrés de liberté articulaire permettrait ainsi de diminuer le nombre de variables à contrôler par le SNC (Horak & Nashner, 1986). Si nous prenons l'exemple du pendule inversé simple, le contrôle de l'équilibre s'effectue principalement par un contrôle au niveau de l'articulation de la cheville et un gel des autres DDL articulaires. Le SNC peut néanmoins mettre en place une plus grande diversité de stratégies posturales pour conserver l'équilibre corporel. Ces dernières peuvent être définies sur la base de l'organisation spatiale et temporelle des différents segments corporels ainsi que sur l'étendue et l'ordre de recrutement des différents muscles activés (Paillard, 2017). Quatre types de stratégies, communément retrouvés dans la littérature, peuvent être employées : la stratégie de cheville (associée au modèle du pendule inversé simple) (Winter, 1995) ; la stratégie de hanche (inclinaison vers l'avant ou l'arrière du tronc) ; la stratégie verticale (abaissement du centre de masse par la flexion des genoux) et la stratégie du pas en avant/arrière (Nashner & McCollum, 1985). La stratégie dite « mixte » se caractérise par l'apparition de mouvements synchrones des différents segments du corps (Horak & Nashner, 1986). Les différentes organisations segmentaires susmentionnées permettent de maintenir la projection du CM à l'intérieur du polygone de sustentation, et ce, notamment par la maîtrise des degrés de liberté articulaire.

La notion de stratégie posturale a été critiquée par certains auteurs (Kugler & Turvey, 2015; Turvey, 2007). Selon eux, la gestion des DDL reposerait davantage sur une interaction simultanée entre les contraintes liées à l'organisme, à l'environnement et à la tâche et ne correspondrait pas à l'exécution d'une « stratégie » particulière qui serait sélectionnée par le SNC selon l'intensité des forces déséquilibratrices (Ferry et al., 2007). Ces auteurs préfèrent plutôt évoquer la notion de « modes de coordinations posturales » pour caractériser les relations de phase entre les différentes articulations impliquées dans le contrôle postural. En effet, la phase relative entre deux oscillateurs résume les coordinations entre deux articulations et

permet directement d'évaluer le couplage entre ces deux articulations (Ferry et al., 2007). Les tâches expérimentales de poursuite de cibles ont largement été utilisées pour étudier ces relations de phase (Ferry et al., 2007). Dans un tel contexte, une coordination posturale caractérisée par une phase relative de 180° (coordination dite « en antiphase ») signifie que l'articulation des hanches et celle des chevilles se déplacent simultanément dans un sens opposé (un peu comme une stratégie dite de hanche). A l'inverse, une phase relative de 0° (coordination dite « en phase ») indique une mobilisation simultanée de l'articulation des hanches et des chevilles dans le même sens. Toute valeur intermédiaire de phase relative traduit une avance ou un retard de phase d'une articulation sur l'autre. Chaque articulation présente des mouvements fonctionnels ne pouvant être séparés des mouvements de l'autre articulation. Ces études montrent que les hanches et les chevilles sont coordonnées. Un mode de coordination posturale émergerait en fonction de l'évolution des contraintes qui pèsent sur le système (Ferry et al., 2007; Shih et al., 2019). Ce mode de fonctionnement est opposé à la sélection d'une stratégie posturale bien définie selon la contrainte imposée. Ceci permet de lever un certain nombre d'ambiguïté concernant la définition des stratégies posturales développées, à l'origine, par Nashner et McCollum (1985). La gestion des DDL ne s'établit pas seulement au niveau articulaire et s'envisage également au niveau musculaire par la mise en œuvre de synergies musculaires par le SNC.

1.1.2.2. Synergies musculaires

L'utilisation des synergies musculaires a été considérée comme une solution au problème de la redondance motrice (Bernstein, 1967) en diminuant le nombre de degrés de liberté au niveau du contrôle. Le principe de synergie musculaire peut être définie comme la coordination fonctionnelle s'établissant entre différents muscles pour produire un mouvement particulier. Les synergies permettent de produire un mouvement organisé, rapide, reproductible, modulable et économique. Chacune de ces synergies est activée selon un pattern temporel spécifique. Le nombre de synergies détermine la complexité et l'élaboration de la commande motrice (Clark et al., 2010). Par exemple le nouveau-né réalise un réflexe de marche automatique à l'aide de deux synergies tandis que la marche autonome nécessite 4 à 5 synergies chez l'homme (Bizzi et al., 2008; Clark et al., 2010). Selon Massion (1992) il existe trois hypothèses concernant l'origine des synergies. Les synergies fixes, déterminées génétiquement, dépendraient de réseaux nerveux précâblés sélectionnés en fonction de l'amplitude et de la nature de la perturbation. Des synergies flexibles, assurées par des réseaux construits ou modifiés par l'apprentissage, permettraient de s'adapter rapidement aux conditions environnementales (elles seraient les plus utilisées lors des corrections de l'équilibre) (Nashner, 1977; Pozzo et al., 1990).

Enfin, des synergies computationnelles intégreraient les afférences sensorielles dans un mécanisme de correction d'erreurs associé à une activation musculaire plus appropriée. Les trois hypothèses se basent sur le même postulat, elles constituent un pattern stable et seul le niveau d'activation est modifié selon le contexte. Les synergies permettent d'accomplir des tâches secondaires, de faire face à de nouvelles contraintes, de réduire les coûts et d'appréhender efficacement les perturbations posturales. En effet, le contrôle postural nécessite la coordination spatiale et temporelle de plusieurs muscles. L'étude des synergies musculaires est généralement associée à un enregistrement de l'activité électromyographique des muscles impliqués dans le contrôle postural et à des dispositifs générant des perturbations de l'équilibre (Torres-Oviedo & Ting, 2007). Ces perturbations, en fonction de leur nature, entraînent des réponses posturales spécifiques qui sont appelées ajustements posturaux (Massion, 1992).

1.1.3. Ajustements posturaux

Les ajustements posturaux précèdent, accompagnent et succèdent tout mouvement volontaire ou toute perturbation (Bouisset, 1991). Selon leur chronologie d'apparition, ces ajustements posturaux ont respectivement été nommés « ajustements posturaux anticipateurs » (APA) (Bouisset & Zattara, 1987), « ajustements posturaux simultanés » (APS) (Bouisset & Zattara, 1987; Fourcade & Memari, 2015) et les « ajustements posturaux consécutifs » (APC) (Arui & Latash, 1995; Bouisset & Zattara, 1987; Fourcade et al., 2018). Dans le cas particulier des perturbations externes, on parle d'ajustement posturaux réactionnels ou de réaction posturale.

1.1.3.1. Ajustements posturaux anticipateurs

Le caractère « anticipé » des ajustements posturaux anticipateurs (APA) a été identifié dans l'étude de Belenkii et al. (1967) portant sur l'élévation du membre supérieur dans une posture orthostatique. Ces auteurs avaient mis en exergue une activation du biceps fémoral (muscle fléchisseur de la jambe et extenseur de la hanche) survenant environ 45 millisecondes avant l'activation du deltoïde antérieur (muscle focal responsable de l'élévation du membre supérieur). Lorsqu'un mouvement volontaire est réalisé à partir d'une posture érigée, deux composantes du mouvement peuvent ainsi être distinguées : une composante focale associée à la partie du corps déplacée intentionnellement et une composante posturale (Bouisset, 1991). Du fait de leur caractère anticipé, les APA ne peuvent pas résulter d'une activité réflexe provenant d'un feedback afférent : ils sont donc centralement préprogrammés et organisés selon un système en « boucle ouverte » (Bouisset & Zattara, 1987, 1981; Massion, 1992).

Les APA participent principalement à minimiser les effets potentiellement déstabilisateurs liés à la réalisation du mouvement volontaire (Massion, 1994), notamment lorsque l'amplitude du

mouvement réalisé est suffisamment élevée pour perturber la stabilité posturale (Bouisset & Zattara, 1987). En plus de cette fonction stabilisatrice, les APA ont aussi un rôle facilitateur à l'action motrice. Lors de l'initiation à la marche par exemple, le recul du CP lors des APA génère une accélération du CM vers l'avant pour participer à la production du mouvement et à l'initiation du premier pas (Laudani et al., 2021; Lee et al., 1990; Winter, 1995).

Une des caractéristiques fondamentales des APA est leur adaptabilité aux contraintes spatio-temporelles qui sont imposées au système postural. Cette adaptabilité est nécessaire au maintien de la stabilité posturale et de la performance motrice (Bouisset et al., 2000; Yiou et al., 2017).

1.1.3.2. Ajustements posturaux simultanés

Les ajustements posturaux simultanés (APS) viennent compléter l'action des APA dans la réalisation du mouvement volontaire. L'étude de Fourcade et Memari (2015) s'est focalisée sur les APS lors d'une tâche de pointage avec le membre supérieur, en posture assise. Les perturbations posturales induites par les mouvements du bras, à partir d'une modélisation 2D puis 3D, ont permis aux auteurs de calculer la quantité d'accélération du membre supérieur par rapport au reste du corps et de distinguer les composantes focales et posturales des APS. Les APA sont assistées par les APS dans leur rôle de contre-perturbation et de propulsion du mouvement. En effet les APS sont aussi programmés en fonction de la vitesse du mouvement volontaire (Fourcade & Memari, 2015).

1.1.3.3. Ajustements posturaux consécutifs

Les ajustements posturaux consécutifs (APC) ont un rôle compensatoire vis-à-vis des APA. Les APC peuvent être considérés comme la contre perturbation nécessaire à la stabilisation ou à l'arrêt du déplacement du CM (Le Bozec et al., 2008).

Selon Fourcade et al. (2018), l'amplitude des APC et des APA augmentent significativement avec la vitesse de mouvement. Kanekar et Aruin (2014) ont montré que les APC permettaient de renforcer l'action contre-perturbatrice des APA ou de remplacer cette action s'il n'y a pas ou peu d'APA. Le mode de contrôle permettant d'assurer la stabilité est alors réactif ou compensateur car il n'y a pas d'opportunité de pré-planifier le mouvement corporel subi : le contrôle se fait par rétroaction, en mettant en place des APC initiés par les signaux sensoriels qui émergent après la perturbation, dans le but de restaurer la position du CM après qu'une perturbation ait déjà eu lieu (Alexandrov et al., 2005 ; Mille et al., 2003 ; Park et al., 2004).

1.2. Neurophysiologie de l'équilibration

1.2.1. Composante sensorielle

La stabilité de l'équilibre est maintenue par l'intégration d'entrées sensorielles d'origine visuelle, vestibulaire et somatosensorielle qui vont permettre de produire une réponse posturale efficace et adaptée aux contraintes rencontrées.

1.2.1.1. Récepteurs visuels

La vision a un rôle prépondérant dans les tâches posturales et locomotrices (Lee & Aronson 1974; Pérennou 2012). Comme on peut le voir sur la figure 3, la suppression des informations visuelles à partir d'une posture orthostatique s'accompagne en effet d'une augmentation des oscillations du corps (Pérennou, 2012).

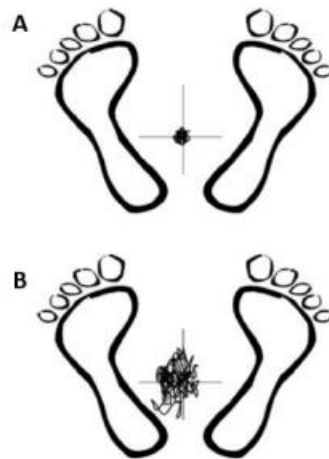


Figure 3 : Statokinésigramme d'un sujet avec les yeux ouverts (A) et les yeux fermés (B) dans d'une station orthostatique d'après Pérennou, (2012)

Les photorécepteurs (cônes et bâtonnets) de la rétine transforment l'information visuelle en influx nerveux qui sera véhiculé par le nerf optique jusqu'au cortex visuel des lobes occipitaux (situés dans la partie postérieure des hémisphères cérébraux) dans lesquels cette information sera traitée (Dupui, 2016). La vision se subdivise en deux sous-systèmes : la vision centrale et la vision périphérique dont la distinction s'opère tant sur le plan anatomique que fonctionnel dans la transmission d'informations de nature statique et dynamique. La vision centrale, aussi appelée la vision fovéale, représente seulement 3° du champ visuel. Elle permet la reconnaissance et la localisation des objets dans l'espace, même de loin (Nakayama & Tyler, 1981). Lors de mouvements d'atteinte et de saisie, la vision centrale participe au codage spatial des segments corporels et des cibles (Biguer et al., 1982). La vision périphérique, quant à elle, possède un champ bien plus large que la vision fovéale. Elle va principalement fournir des

informations dynamiques en permettant notamment la perception du mouvement et renseigner le SNC sur les vitesses et les trajectoires (Amblard et al. 1985 ; Lestienne et al., 1977). Le déroulement d'une scène hétérogène dans le champ visuel périphérique provoquera un réflexe optocinétique qui fixera le regard sur une cible en mouvement en provoquant des mouvements oculaires alternant poursuite et saccades de recentrage (Paillard, 2016). L'entrée visuelle renseigne, entre autres, le SNC sur l'orientation du corps dans l'espace à travers la perception de la verticale (Isableu et al., 1997). La contribution visuelle est prépondérante dans une situation d'équilibre plus contraignante (posture de Romberg, position monopodale, support en mousse, plateforme de force sinusoïdale).

Plusieurs types d'informations en provenance de la vision vont contribuer à la régulation de l'équilibre postural. En 1966, Gibson distinguait les informations « extéro-spécifiques » (formes des objets et vitesse relative) et les informations « proprio-spécifiques » (renseigne le sujet sur son propre mouvement). Ces informations procurent à la vision un sens kinesthésique qui renseigne le SNC sur la direction et la vitesse de déplacement du corps. La vision joue également un rôle prépondérant dans l'apparition des ajustements posturaux. Krishnan & Aruin (2011) ont démontré dans leurs travaux que lorsque les participants étaient privés de vision, aucune anticipation n'était possible ; les APA étaient quasiment absents mais compensés par des APC. Les informations visuelles contribuent donc à la double fonction du contrôle postural, à savoir la fonction stabilisation et d'orientation du corps dans l'espace. Le glissement rétinien est optimisé par le réflexe vestibulo-oculaire qui assure la stabilisation de la tête lors du mouvement (Feldman & Zhang, 2020).

1.2.1.2. Récepteurs vestibulaires

Le système vestibulaire constitue une véritable centrale inertielle de guidage qui renseigne le SNC sur la position et les mouvements de la tête dans l'espace à l'instar d'un gyroscope (Berthoz 2010).

D'un point de vue anatomique, le système vestibulaire est situé au niveau de l'oreille interne. Il se compose d'un labyrinthe antérieur cochléaire (organe de l'ouïe) et d'un labyrinthe postérieur vestibulaire (le vestibule et les trois canaux semi-circulaires). Le saccule et l'utricule, situés dans le vestibule, constituent le système otolithique. Le premier va être sensible aux accélérations linéaires verticales et le second aux accélérations linéaires horizontales. Ce complexe va donc être sensible au vecteur gravitationnel (qui stimule en permanence le saccule) et va renseigner le SNC sur la verticalité (Keshner & Cohen, 1989; Nashner & McCollum, 1985). Le système canalaire, quant à lui, donne des indications sur les accélérations angulaires

du segment céphalique autour des trois directions de l'espace (verticale, médiolatérale, antéropostérieure). Relié de part et d'autre à l'utricule, chaque canal est composé de petits cils sensitifs, dans lequel circulent des liquides nommés endolymphes et périlymphe qui sont nécessaires à l'audition et à l'équilibration. A cet égard, l'audition représente aussi une entrée sensorielle qui participe, dans une moindre mesure, à la régulation posturale (Seiwerth et al., 2020). La dichotomie entre ces deux accéléromètres ne se résume pas à la nature des accélérations qu'ils captent (linéaire ou angulaire). Il semblerait que le système otolithique soit prédisposé à la détection des oscillations de basses fréquences alors que les canaux semi-circulaires seraient plus enclins à la détection des oscillations de haute fréquence (Nakagawa et al., 1993; Nashner & Berthoz, 1978). Les accélérations du segment céphalique en posture debout non perturbée sont inférieures au seuil de sensibilité des canaux semi-circulaires. En effet ces récepteurs sont sensibles aux accélérations angulaires dans le plan de 2 canaux, les canaux horizontaux étant les plus sensibles (seuil : $0,14^\circ \cdot s^{-2}$), les autres ayant un seuil moyen de $0,5^\circ \cdot s^{-2}$. Cela pourrait expliquer cette faible participation (Fitzpatrick et al., 1994; Fitzpatrick & McCloskey 1994). Toutefois, lorsque les informations fournies par les autres systèmes sont réduites, imprécises ou indisponibles, le système postural s'appuie davantage sur les signaux vestibulaires (Fitzpatrick & McCloskey, 1994; Shumway-Cook & Horak, 1986). De manière intrinsèque, le système vestibulaire est davantage sollicité lors de la locomotion. De plus, il assure l'orientation du haut du corps et à la stabilisation du regard via les réflexes vestibulo-spinaux et vestibulo-oculaires (Appiah-Kubi & Wright, 2019). En revanche, lorsque le corps est déstabilisé par des perturbations externes, le poids relatif du système vestibulaire est moins important que celui des informations somatosensorielles (Horak et al., 1994).

1.2.1.3. Récepteurs somato-sensoriels

La somesthésie est un système ubiquitaire qui participe activement au contrôle de la posture. Il s'agit d'une véritable interface permettant les interactions entre le corps et son environnement. Elle se compose de trois sous-systèmes : la proprioception, l'intéroception et l'extéroception (Paillard, 2021). En 1906, Sherrington a fait la distinction entre les sens somatiques (extérocepteurs, propriocepteurs) et les sens viscéraux (intérocepteurs) dans sa classification des sens (Sherrington, 1906). L'intéroception renseigne le SNC sur l'état viscéral du corps (sensation de soif, de faim, douleur et température corporelle). Le système somatosensoriel perçoit donc les sensations émanant de la peau via les extérocepteurs (sensation au toucher, à la pression, à la vibration, à la chaleur, au froid et à la douleur) ainsi que celles des tissus profonds (position, mouvements, tension) via les propriocepteurs (Sherrington, 1906; Stillman,

2002). La fonction de ces mécanorécepteurs varie selon leurs caractéristiques et leurs localisations.

Les fuseaux neuromusculaires (FNM), innervés par les fibres de type Ia et II, sont fusiformes et attachés au tissu conjonctif intra-musculaire. Ces mécanorécepteurs vont percevoir la vitesse d'étirement du muscle, être sensibles à la variation de sa longueur, et contribuer à la localisation et l'orientation des segments corporels dans l'espace par des informations statiques et dynamiques (Proske, 1997; Proske & Gandevia, 2012). Les FNM, stimulés via l'activation des motoneurones γ , assurent la fonction antigravitaire notamment par la contraction des muscles extenseurs. Par ailleurs les FNM interviennent dans la mise en jeu du réflexe myotatique lors d'un étirement passif ou actif d'un muscle. Ce mécanisme protège le muscle contracté et limite son amplitude d'étirement (Paillard, 2021).

Les organes tendineux de Golgi (OTG), situés au niveau de la jonction myotendineuse, sont sensibles aux variations de tension tendineuse, que ce soit lors d'un étirement passif ou d'une contraction volontaire. Comparés au FNM, les OTG sont des récepteurs plus basiques composés d'une seule connexion afférente (fibre Ib) et dépourvus de fibres efférentes (Proske & Gandevia 2012). Au-dessus d'une certaine tension exercée au niveau de la jonction myotendineuse le capteur se déforme et déclenche un stimulus codant le niveau de tension exprimé à ce niveau. Le rôle des OTG est de réduire l'activité des motoneurones α du muscle sollicité. Dès lors, les fibres Ib innervant ces motoneurones via un interneurone inhibiteur vont réguler la tension musculaire en présence de forces excessives. Ce mécanisme est responsable du réflexe myotatique inverse qui évite une trop grande tension en provoquant une inhibition des motoneurones excitateurs des muscles contractés (Paillard, 2021).

Les récepteurs articulaires sont, quant à eux, sensibles à la position et à la vitesse de rotation des articulations. On distingue des récepteurs extra-capsulaires, les organes ligamentaires de Golgi (sensible à la tension ligamentaire) et les corpuscules ligamentaires de Pacini (sensibles aux accélérations) et des récepteurs intra-capsulaires composés des organes terminaux de Ruffini (sensibles aux positions extrêmes de l'articulation et aux mouvements de rotation) (Paillard, 2021).

Les mécanorécepteurs cutanés sont à l'origine du tact épicrotique. Ces récepteurs réalisent la transduction et le codage de la qualité, de l'intensité, de la durée et de la localisation d'un stimulus. Ils répondent à des stimuli de différentes natures (pression, toucher, vibration et l'étirement de la peau) et de différentes intensités. Ils possèdent des vitesses d'adaptation et de

conduction (de 40 à 75m/s) qui diffèrent selon le type de récepteurs (Johnson, 2001). La vitesse d'adaptation est définie comme une perte progressive de la sensibilité des récepteurs lorsque la stimulation est maintenue constante pendant un certain temps. La répartition ainsi que la densité des mécanorécepteurs varient selon les caractéristiques physiologiques de la peau (glabre ou velue) et leur localisation (médiale ou latérale). Cinq types de récepteurs mécaniques sont répertoriés : le disque de Merkel, les corpuscules de Meissner, de Ruffini, de Pacini et les terminaisons libres (Owens & Lumpkin, 2014). On distingue les récepteurs à adaptation lente (disque de Merkel, corpuscules de Ruffini) qui renseignent sur la valeur absolue de l'intensité du stimulus et sa durée et les récepteurs à adaptation rapide (corpuscules de Meissner et Pacini) qui traduisent les variations du stimulus en fonction du temps (Garrison et al., 2012). Cependant une classification plus précise peut-être établie selon les afférences cutanées à adaptations rapides (FA) et lentes (SA) de type I (FAI et SAI) ou type II (FAII et SAII) en fonction des caractéristiques de leurs champs récepteurs. Le champ récepteur désigne la zone anatomique qui, lorsqu'elle est soumise à un stimulus environnemental, va modifier l'activité de son récepteur sensoriel. Ainsi nous avons :

- Les disques de Merkel, à adaptation lente de type I (afférence SAI). Ils sont localisés dans la couche basale de l'épiderme. Ils ont une vitesse de conduction lente (40-70 m/s). Ces récepteurs toniques sont caractérisés par une décharge maintenue tout au long du stimulus et possèdent un champ récepteur restreint (2 à 3 mm²) (Johnson, 2001).
- Les Corpuscules de Ruffini, à adaptation lente (afférence SAII). Ce sont des récepteurs toniques avec un champ récepteur étendu. Ils sont localisés profondément dans le derme de la peau glabre et non glabre et ils ont une vitesse de conduction lente (50-70 m/s). Ils sont sensibles à l'étirement de la peau et possèdent grand champ de récepteurs (Cobo et al., 2021).
- Les Corpuscules de Meissner. Ce sont des récepteurs à adaptation rapide (afférence FAI), localisés dans les papilles dermiques de la peau glabre. Ces récepteurs phasiques sont caractérisés par une réponse rapide impliquant une décharge maximale mais brève et une diminution de la réponse si le stimulus est maintenu. Ils ont une vitesse de conduction rapide (54-60 m/s) et répondent aux stimuli sur l'ensemble de leurs champs réceptifs (3-5 mm de diamètre). Ils sont insensibles à la déformation statique de la peau et sont quatre fois plus sensibles à la déformation dynamique de la peau comparativement aux afférences de type SAI. Les corpuscules de Meissner sont

particulièrement sensibles aux mouvements dans leurs champs récepteurs et les afférences FAI peuvent coder de façon fiable la vitesse de déplacement à travers la peau (Cobo et al., 2021).

- Les Corpuscules de Pacini. Ce sont des récepteurs à adaptation rapide (afférence FAII) localisés à travers le derme et le tissu sous-cutané à la fois poilu et glabre. Ce sont des récepteurs phasiques qui ont une vitesse de conduction rapide (57-75 m/s) avec un champ récepteur étendu et qui sont extrêmement sensibles aux vibrations à haute fréquence (Cobo et al., 2021).
- Les terminaisons libres. Elles sont localisées dans l'épiderme et elles ont une vitesse de conduction relativement rapide. Ce sont des récepteurs toniques qui possèdent un champ récepteur restreint (Johnson, 2001).

L'ensemble de ces récepteurs contribuent non seulement au sens du toucher dans la reconnaissance tactile des objets mais renseignent le SNC des déformations statiques et dynamiques de la peau. Les informations tactiles (notamment cutanées plantaires) jouent un rôle prépondérant dans le contrôle de la posture. Les manipulations expérimentales qui perturbent cette entrée sensorielle (e.g. utilisation de supports compliants, anesthésie, ischémie, hypothermie) s'accompagnent d'un accroissement significatif de l'instabilité posturale (McKeon & Hertel, 2007; Peter et al., 2004; Thoumie & Do, 1996). Ces résultats montrent que les mécanorécepteurs cutanés sont une composante incontournable du mécanisme de contrôle de l'équilibre.

1.2.1.4. Le poids relatif des entrées sensorielles

En position orthostatique, les personnes saines s'équilibrent en se basant sur les informations provenant des diverses modalités sensorielles (Figure 4). Selon Horak (2006), le contrôle postural est un processus qui s'établit en accordant une importance plus ou moins marquée aux différentes informations sensorielles. Selon Peterka (2002, 2018), le poids relatif des différentes entrées sensorielles impliquées dans la régulation de l'équilibre en position orthostatique serait le suivant : 50% pour les informations somato-sensorielles, 33% pour la vision et 17% pour les informations vestibulaires.

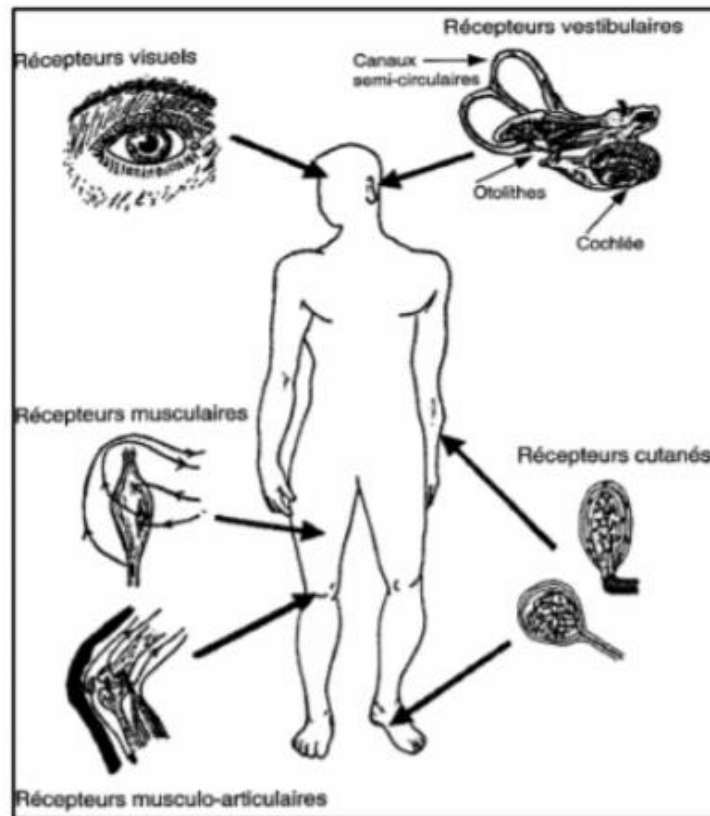


Figure 4 : Multimodalité sensorielle (Berthoz, 1997)

Les informations sensorielles sont intégrées par des mécanismes qui ne se réduisent pas à privilégier un type d'afférence ou à faire la somme de toutes les entrées disponibles. Ils reposent au contraire sur une modulation continue du poids attribué à chaque entrée sensorielle par le biais de phénomènes de pondération et de repondération sensorielle (Nashner et al., 1982). Ce sont des processus actifs qui vont être liés à la disponibilité et à la fiabilité des différentes informations sensorielles (Barela et al., 2014, 2003; Jeka et al., 2008; Peterka, 2002). Lorsqu'il y a une perturbation d'origine interne (troubles neurologiques) ou externe (modification de l'environnement), le SNC sélectionne et augmente la contribution des informations qu'il juge comme étant fiables et nécessaires au maintien de l'équilibre, tout en négligeant celles qui ne sont pas fiables ou indisponibles (Carver et al., 2006). L'influence de chaque modalité sur le contrôle postural varie ainsi selon la tâche, le contexte environnemental, les conditions biomécaniques et les spécificités individuelles pour s'adapter à toutes ces contraintes (Kavounoudias et al., 2001).

La capacité de repondération sensorielle a été mise en évidence dans les études de manipulation sensorielles (Horak 2006, 2009 ; Horlings et al., 2008 ; Kavounoudias et al., 2001 ; Lord et al., 1999 ; Peterka 2002). En cas de privation visuelle sur un support fixe, un mécanisme

d'adaptation favorisant l'utilisation des indices proprioceptifs est mis en place. Sur un support mobile, les sujets utilisent davantage les informations vestibulaires pour mettre en place des ajustements permettant de conserver l'équilibre (Peterka, 2002; Polastri et al., 2012). En cas de perturbation d'une entrée sensorielle, le SNC peut donc mettre en place des phénomènes compensatoires grâce à cette capacité de repondération sensorielle et ainsi éviter des perturbations de l'équilibre trop importantes pouvant entraîner une chute ou une perturbation de l'équilibre postural (Fransson et al., 2003; Goodworth et al., 2018; Jeka et al., 2008; Peterka, 2002). Lorsque les afférences cutanées plantaires sont altérées, par l'application prolongée de froid ou l'utilisation d'un support compliant (e.g. support en mousse), cela augmente la contribution des entrées visuelles (Hong et al., 2007; Patel et al., 2011; Polastri et al., 2012). Un mécanisme compensatoire similaire est observé lorsque les entrées proprioceptives sont faussées par l'utilisation de vibrations musculaires ou tendineuses (Fransson et al., 2003; Radhakrishnan et al., 2011). L'altération des indices visuels induite par l'application de technique optocinétique augmente le poids des indices proprioceptifs pour apprécier les mouvements du corps relatifs au support et mettre en place les ajustements posturaux adéquats (Polastri et al., 2012). Le processus de pondération entraîne une contribution plus importante des entrées proprioceptives et visuelles lors d'une stimulation vestibulaire galvanique (Fransson et al., 2003). Enfin, il semble également que les processus cognitifs interviennent dans les mécanismes de repondération puisque la connaissance explicite ou implicite de la manipulation sensorielle conduisent toutes les deux à des adaptations, qui sont plus importantes lorsque la connaissance est implicite (Barela et al., 2014).

1.2.2. Composante centrale

A la suite des travaux de Magnus et De Kleijn (1926) qui observèrent la persistance de réflexes spinaux pour maintenir une posture malgré l'inhibition des entrées corticales afférentes, le contrôle postural a été longtemps considéré comme une somme de réflexes régulés au niveau sous-cortical. Or nous savons désormais qu'il implique une participation des structures spinales et supra-spinales.

1.2.2.1. Intégration spinale

D'un point de vue fonctionnel, le contrôle spinal (aussi appelé médullaire) s'effectue via l'activité réflexe somatique, dont la moelle épinière constitue le lieu d'intégration. Enfermée dans la colonne vertébrale, elle est connectée à 31 nerfs rachidiens bilatéraux (nerfs mixtes c'est-à-dire à la fois sensitifs et moteurs) qui assurent la connexion entre le SNC et les différents

segments corporels. Les informations qui transitent par ces nerfs circulent dans les deux sens le long des voies ascendantes (afférentes ou sensorielles) et descendantes (motrices ou efférentes).

Les informations sensorielles issues des différents récepteurs cutanés, articulaires, musculaires et tendineux se projettent à différents étages médullaires pour créer des boucles réflexes segmentaires courtes qui vont, très rapidement, modifier (renforcer ou au contraire inhiber) l'activation tonique des motoneurons des muscles posturaux et vont donc permettre des ajustements du tonus musculaire. Cette intégration spinale correspond à une boucle courte qui facilite l'activation des motoneurons des muscles posturaux par voie réflexe (Paillard, 2021). C'est ainsi que la moelle épinière peut générer, sans l'intervention des structures supra-spinales, des commandes motrices rythmiques impliqués notamment dans la locomotion (réflexe de marche du nourrisson) ainsi que des réponses motrices autonomes par le biais des réflexes spinaux. Un réflexe est une réponse motrice rapide, prévisible, automatique et involontaire à un stimulus ; il peut être inné ou acquis (Marieb, 2005). Ici, les stimuli sont des informations périphériques musculaires (telles que l'amplitude et la vitesse d'étirement du muscle ainsi que la tension qu'il génère) ou cutanés (informations nociceptives). Les informations intégrées au niveau spinal sont à l'origine du réflexe myotatique (ou réflexe d'étirement), du réflexe myotatique inverse (ou réflexe tendineux), du réflexe d'inhibition réciproque (relâchement du muscle antagoniste lors de la contraction de l'agoniste), du circuit de Renshaw (fonction inhibitrice ou désynchronisatrice), du réflexe de flexion ipsilatérale et du réflexe d'extension croisée (lors de la perception de stimuli nociceptifs). Les voies descendantes assurent également la transmission de l'information efférente émanant des structures supérieures.

1.2.2.2. Intégration supra-spinale

Le contrôle postural est régi par les structures supra-spinales. L'encéphale est constitué des hémisphères cérébraux, du diencéphale (thalamus, hypothalamus et épithalamus), du tronc cérébral (mésencéphale, pont et bulbe rachidien) et du cervelet. Le cortex cérébral correspond à la partie superficielle des hémisphères cérébraux. Ces structures correspondent au centre de contrôle qui reçoit les afférences sensorielles, les traite, initie et contrôle le mouvement. Ainsi, la régulation de la posture et de l'équilibre suit différentes étapes (Figure 5).

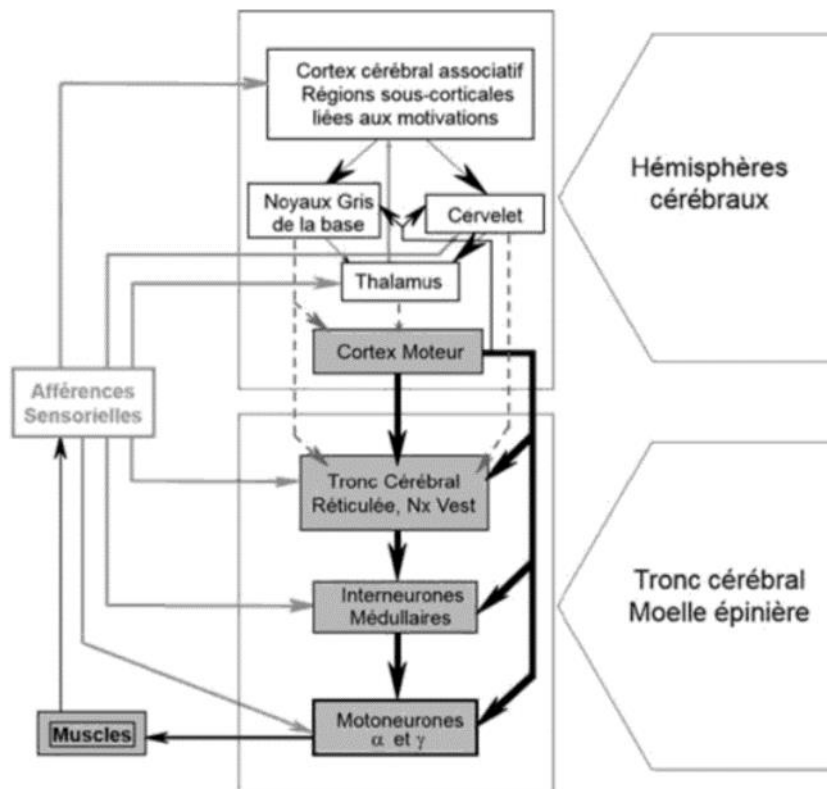


Figure 5 : *Systèmes sensorimoteurs impliqués dans le contrôle postural (Dupui, 2016)*

Les voies efférentes, ou motrices, véhiculent les ordres du SNC vers la périphérie, via deux voies de projection : les voies pyramidale et extrapyramidale. La voie pyramidale croisée se projette directement sur les neurones spinaux après avoir décussé au niveau bulbaire et contrôle l'exécution de gestes fins et précis. La voie extrapyramidale forme un ou plusieurs relais synaptiques dans des structures sous corticales, avant de se terminer sur les corps cellulaires de motoneurones α et γ (qui assurent l'activité motrice et le tonus musculaire), permettant ainsi l'adaptation tonique de la musculature striée squelettique.

Plusieurs études mettent en exergue l'implication corticale au niveau du contrôle postural, notamment les expérimentations avec des sujets atteints de pathologies. En effet, chez les sujets atteints d'anomalies neurologiques telles qu'un syndrome extrapyramidal ou une maladie dégénérative (comme Alzheimer ou Parkinson), on observe un accroissement exponentiel de l'incidence des chutes (Allan et al., 2005; Doná et al., 2016).

1.2.3. Composante motrice

Les structures motrices neuromusculaires constituent les principaux effecteurs de la motricité somatique et sont indispensables au maintien du contrôle de la posture. On distingue communément les muscles dits toniques, responsable principalement du maintien de la posture

et les muscles dits phasiques qui assurent principalement le mouvement. Selon leur fonction, les muscles striés squelettiques n'ont pas la même composition, ils peuvent être constitués principalement de fibres de type I (toniques, rouges) à métabolisme aérobie ou de fibres de type II (phasiques, blanches) majoritairement à métabolisme anaérobie. D'une manière générale, l'ensemble des fibres musculaires chez l'homme est réparti de la sorte : 53% de fibre de type I, 33% de fibre IIa et 14% de fibre IIx (Schiaffino & Reggiani, 2011). Ainsi, nous pouvons observer une dichotomie entre les muscles posturaux tels que le soléaire qui peut compter jusqu'à 80% de fibres de type I et les muscles du mouvement tel que le biceps brachial dont le pourcentage de fibre de type II est nettement supérieur. Chaque fibre musculaire reçoit une innervation motrice transmise par l'axone d'un neurone dont le corps cellulaire est situé dans la corne antérieure de la moelle épinière. Un motoneurone α active simultanément l'ensemble des fibres qu'il innerve (de même typologie). Cet ensemble structurel se nomme unité motrice (UM) (Sherrington, 1906). En outre, le nombre de fibres par UM est inversement proportionnel à la précision des mouvements qu'il génère. De plus, la force produite est proportionnelle au nombre d'UM activées. Le recrutement des unités motrices est régi par la loi d'Henneman. Ainsi, lors de la propagation de l'influx nerveux (potentiel d'action), les unités motrices sont recrutées de façon ordonnée selon leur typologie. Les fibres de type I sont toujours recrutées avant les fibres de type IIa, dont le recrutement précède toujours le recrutement des fibres de type IIx (Henneman et al., 1965). À faible intensité, les unités motrices de petit calibre (type I) sont les premières recrutées car les petits neurones moteurs sont plus excitables que les gros neurones. Si l'intensité augmente, les unités motrices de gros calibre (type II) sont alors recrutées pour produire une contraction musculaire plus intense. Cet ordre de recrutement est inéluctable pour une contraction volontaire, seul l'électrostimulation déroge à la règle et entraîne un recrutement aléatoire des UM (Gregory & Bickel, 2005). Les fibres de type I sont présentes en grande proportion dans les muscles posturaux et le caractère peu fatigable de ces fibres leur permet d'assurer leur fonction antigravitaire.

1.3. Plasticité de la fonction posturale et différences interindividuelles

1.3.1. *Préférences sensorimotrices et expertise motrice*

Les processus de pondération dépendent de facteurs interindividuels tels que l'expérience, la pratique d'activité physique, l'âge et l'intégrité du système neuromusculaire qui vont influencer sur la capacité du SNC à pondérer les entrées sensorielles. On peut ainsi faire la différence entre des adaptations dites « dynamiques rapides » (courte période transitoire au cours d'une session expérimentale) et des adaptations plus lentes dites « dynamiques lentes » qui sont induites sur

le long terme à travers des expériences sensorimotrices d'un individu (Chiba et al., 2016). Le poids relatif accordé à chacune des entrées sensorielles dépend également des objectifs de la tâche et du contexte environnemental (Horak, 2006) et diffère selon les individus. Les sujets « dépendant du champ » utilisent principalement la vision tandis que les sujets « indépendants au champ » se réfèrent plutôt au système vestibulaire et/ou somesthésique dans la perception de la verticale. Ainsi, le mode de perception de la verticale, l'orientation du corps dans l'espace, varie non seulement selon les situations, mais également selon les individus et leurs expériences motrices (Chiba et al., 2016; Horak, 2006).

L'expérience motrice, selon Paillard (2017), génère des adaptations structurelles et fonctionnelles de la fonction posturale. Ces expériences sensorimotrices vont contribuer à développer une représentation interne chez l'individu appelée, schéma corporel. Massion (1994) attribue au schéma corporel une double fonction d'orientation et de stabilisation lors du contrôle postural. Chez les sportifs, la répétition d'actions motrices spécifiques module leur contrôle postural. Paillard et al. (2007) ont mis en évidence que les judokas qui avaient comme préférence les techniques de projections en appui bipodale (e.g. Ippon-Seoi-Nage) avaient un meilleur contrôle postural en condition dynamique standardisée sur deux appuis que les judokas qui préféraient les projections sur un appui (e.g. Hane-Goshi) et réciproquement. Chez les judokas, la stimulation répétée des afférences cutanées plantaires durant les entraînements et combats induit par ailleurs une pondération des entrées sensorielles en faveur des récepteurs somatosensoriels (Perrin et al., 2002). Certains auteurs ont observé une amélioration de la proprioception articulaire chez les sportifs exerçant le taekwondo et le volley-ball (Paillard, 2017). Cette amélioration serait liée à une augmentation la sensibilité des capteurs proprioceptifs (FNM, OTG, les récepteurs articulaires) et une réorganisation corticale qui assurerait un meilleur traitement central des informations proprioceptives (Han et al., 2015). La plupart des expériences motrices (e.g. sports collectifs, sports de combat) permettent aux sportifs de diminuer leur dépendance visuelle pour contrôler leur posture de sorte que la vision peut être consacrée à la prise d'informations émanant du jeu ou du combat (Paillard et al., 2006). A l'inverse les non-sportifs sollicitent davantage l'entrée visuelle que les sportifs de haut niveau pour contrôler leur équilibre (Paillard et al., 2006; Perrin et al., 2002). En utilisant une stimulation vestibulaire galvanique, Balter et al., (2004) ont observé que les gymnastes n'avaient pas un système vestibulaire plus sensible que les sujets non entraînés mais qu'ils apprenaient plutôt à mieux utiliser les différentes entrées sensorielles, ce qui suggère une meilleure intégration centrale (Hartmann et al., 2014; Maitre and Paillard, 2016). L'exigence

de la tâche et l'environnement de pratique peuvent également modifier les stratégies sensorimotrices des individus. Powell et Williams (2015) ont comparé l'équilibre postural de sujets habitués à s'entraîner sur une surface stable à celui d'athlètes habitués à s'entraîner sur une surface instable. Leurs résultats ont révélé que les athlètes qui s'entraînaient sur une surface stable (e.g. terrain de basket) utilisaient une stratégie ascendante de distal à proximal alors que les athlètes s'entraînant sur une surface instable (e.g. planche de surf, snowboard) utilisaient plutôt une stratégie descendante de proximal à distal.

1.3.2. Asymétries fonctionnelles

1.3.2.1. Origine des asymétries

Bien que les hémisphères gauche et droit de notre cerveau se développent avec un haut degré de symétrie, tant au niveau anatomique que fonctionnel, des différences structurelles subtiles existent entre les deux côtés et un hémisphère peut être dominant dans le traitement de tâches cognitives spécifiques (Duboc et al., 2015). Il existe notamment des spécialisations hémisphériques pour les aspects clés du langage et de la fonction motrice (Gutnik et al., 2015). Des asymétries fonctionnelles peuvent ainsi caractériser certains aspects de la fonction motrice et la proprioception (Duboc et al., 2015). Concernant les afférences proprioceptives, il semblerait qu'il y ait une dominance du système bras/hémisphère non préférés dans l'utilisation de la rétroaction proprioceptive chez les droitiers (Goble et al., 2006). L'étude de Han et al. (2013) confirme et complète cette précédente étude. Les données démontrent une asymétrie latérale générale, en termes de supériorité de la tâche proprioceptive du côté gauche, au niveau de plusieurs articulations des membres supérieurs et inférieurs. Cette spécialisation du système bras/hémisphère non préféré dans l'utilisation du feedback proprioceptif a été attribuée aux différences fonctionnelles entre les rôles des bras préférés et non préférés dans les tâches bimanuelles (Goble et al., 2009).

Chez certains sujets il est possible d'observer des asymétries d'équilibre entre les membres inférieurs. Pour évaluer ces asymétries posturales entre chaque appui, les déplacements du CP sont enregistrés par deux plateformes de force ce qui permet d'obtenir des données inhérentes à chaque membre (Gentson et al., 2009). Ces asymétries sont principalement liées à des différences de traitement somatosensoriel entre les deux jambes provenant d'une asymétrie hémisphérique cérébrale (Liu et al., 2021; Marcori et al., 2019; Promsri et al., 2019, 2018). L'asymétrie sensori-motrice peut directement être observée au niveau de l'utilisation d'une main, d'un pied, d'un œil, ou même d'une oreille préférentielle dans la vie quotidienne. Cette latéralisation entraîne indéniablement une dominance d'un segment par rapport à l'autre (Ho et

al., 2018; Kim et al., 1993; Marcori et al., 2019; Sainburg, 2014; Schneiders et al., 2010). La présence de ces asymétries est multifactorielle ; les pathologies (AVC, scolioses, sclérose en plaques), la croissance asynchrone, les blessures et l'expérience motrice sont également responsables de la présence de différences structurelles/fonctionnelles inter membres et peuvent avoir des répercussions sur l'expression des qualités physiques et potentiellement impacter le contrôle de l'équilibre (Berenguer-Rocha et al., 2020; Bishop et al., 2018; Pau et al., 2021; Yang et al., 2013).

1.3.2.2. Asymétries et contrôle de l'équilibre

La majorité des individus utilisent préférentiellement la jambe dominante pour effectuer des mouvements ou des tâches motrices dynamiques (comme taper dans un ballon) tout en utilisant la jambe non dominante pour stabiliser la posture (Huurnink et al., 2014). La comparaison posturale entre les membres (c'est-à-dire la jambe dominante par rapport à la jambe non dominante) a été étudiée par de nombreux auteurs, mais leurs résultats diffèrent et ne permettent pas de dégager un consensus chez les sujets adultes en bonne santé (Paillard, 2017). Les effets des asymétries sur le contrôle postural seraient dépendants du public choisi et notamment de l'expérience motrice des sujets. Paillard (2017) précise que l'expérience motrice génère des adaptations structurelles et fonctionnelles de la fonction posturale. Ainsi la pratique de sports dit « asymétriques » peut entraîner une sollicitation récurrente d'un côté du corps (Paillard & Noé, 2020). C'est le cas pour les activités sportives comme le football ou le handball (Paillard et al., 2006; Paillard & Noé, 2020). Les joueurs tirent, lancent avec leur bras dominant et s'appuient, prennent impulsion avec leur jambe non dominante à chaque entraînement/compétition, ce qui peut entraîner un renforcement de certains patterns moteurs et expliquer les différences de performances posturales entre les deux jambes. De même, le niveau d'expertise pourrait exacerber la différence en termes de performance posturale entre la jambe dominante et la jambe non dominante (Paillard, 2017), d'autant plus si le sportif a fait preuve d'une spécialisation précoce (Marchetti et al., 2012; Miller et al., 2017). Ainsi, les footballeurs et danseurs professionnels ont montré des différences d'équilibre entre leurs deux jambes, alors que leurs homologues novices ne présentaient aucune différence (Lin et al., 2013; Ricotti et al., 2013). Chez les sportifs de haut niveau, le moment de la saison sportive peut également influencer les asymétries posturales. En suivant une équipe de handballeurs professionnels pendant une saison complète, Marchetti et al. (2014) ont montré que les joueurs présentaient des niveaux d'asymétries plus marqués en fin de saison sportive.

Les asymétries inter-membres peuvent avoir un impact négatif sur la performance sportive et sont souvent associées à une incidence élevée de blessures au niveau des membres inférieurs, en particulier si les asymétries concernent le contrôle de l'équilibre (Bishop et al., 2018; Brown et al., 2017; Hrysomallis, 2011; Promsri et al., 2019). Le dépistage d'une asymétrie posturale marquée peut donc être intéressant pour prévenir d'éventuelles blessures (Brown et al., 2018).

2. Stimulation tactile et contrôle de l'équilibre

2.1. Aspects mécanistiques

2.1.1. *Optimisation du contrôle de l'équilibre par stimulation des afférences cutanées*

Les récepteurs tactiles sont extrêmement sensibles et réagissent aux déformations mécaniques de la peau. Leur distribution et leur densité varient selon la région considérée (Kennedy & Inglis, 2002). Prenons comme exemple la main et le pied. Nous pouvons constater que le pied est constitué d'une densité importante de mécanorécepteurs (majoritairement à adaptation rapide) dans la sole plantaire (Figure 6). Le seuil d'activation des mécanorécepteurs cutanés est plus élevé au niveau de la sole plantaire que de la face palmaire car la peau est plus épaisse et les champs récepteurs sont en moyenne trois fois plus grands au niveau du pied comparativement à la main. En effet, plus le champ récepteur est étendu, plus l'acuité tactile est faible. Par exemple, contrairement aux doigts de la main, il n'y a pas d'accumulation des récepteurs SA au niveau des orteils (Vibert et al., 2005). Cette différence s'explique par le rôle distinct de la main et du pied. La main a besoin d'informations précises sur la déformation de la peau pour la prise et le maintien des objets. Le pied, quant à lui, a essentiellement un rôle de support. Néanmoins, les récepteurs présents sur les bords latéral et médial du pied sont majoritairement des récepteurs SA I (disques de Merkel) qui ont un petit champ récepteur et donc un seuil d'activation assez bas (Kennedy & Inglis, 2002). Kennedy et Inglis (2002) ont identifié 104 mécanorécepteurs cutanés renfermés dans l'épaisseur de la peau glabre du pied dont une large proportion à adaptation rapide. Ils ont aussi observé que de larges champs récepteurs sont situés dans la région métatarso-phalangienne (Figure 6).

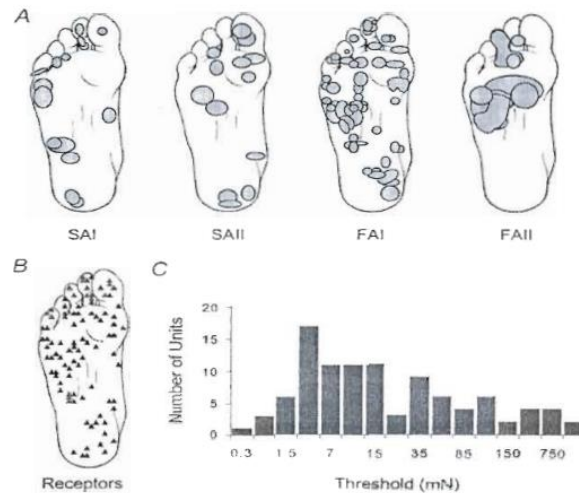


Figure 6 : Les mécanorécepteurs de la sole plantaire selon Kennedy et Inglis (2002)

Sachant que la sole plantaire est l'interface directe entre le sol et le corps humain, toutes les informations cutanées provenant de cette zone renseignent sur les caractéristiques du support ainsi que sur les déplacements du centre de pression. L'absence de réponse des mécanorécepteurs cutanés lorsque le pied est en décharge souligne le fait que toute activité de ces mécanorécepteurs cutanés est importante et rend compte de la moindre évolution du contact entre le pied et le sol (Kavounoudias et al., 2001; Kennedy & Inglis, 2002). Plusieurs tests permettent d'évaluer la sensibilité cutanée plantaire. Le test du seuil de perception à la pression (monofilaments de Semmes-Weinstein) permet d'évaluer la capacité du sujet à discriminer une pression. La fiabilité du test est bonne (Menz et al., 2006) mais les résultats restent soumis à des variations interindividuelles importantes et dépendent largement du ressenti du patient face à ce stimulus. C'est une technique très utile pour évaluer la perte de sensibilité chez la personne âgée (Perry et al., 2008). Son évaluation pourra être complétée par les tests de sensibilité de Weber, de Dellon ou encore le test du diapason de Rydel-Seiffer (Spicher & Roll, 2003).

Le pied est donc un pourvoyeur d'informations somesthésiques variées (mécaniques, thermiques, chimiques, nociceptives) qui vont permettre de gérer la station érigée verticale propre à l'Homme (Roll et al., 2002). Les études portant sur les manipulations d'entrées sensorielles ont mis en évidence des augmentations significatives des oscillations posturales lorsque que la sensibilité cutanée plantaire est altérée (McKeon & Hertel, 2007; Peter F. Meyer et al., 2004; Thoumie & Do, 1996). En revanche, un touché tactile mécaniquement insignifiant au niveau de l'index permet par exemple de réduire les oscillations posturales (Jeka et al., 2008; Jeka & Lackner, 1994; Krishnamoorthy et al., 2002). Collins et al. (2005) ont stimulé les récepteurs cutanés à l'aide d'un ruban adhésif, associés à des vibrations musculaires au niveau

des articulations de l'index, du coude et du genou. L'étirement progressif de la peau pendant la vibration a augmenté de manière significative la sensation de mouvement perçue par rapport à l'étirement cutané seul ou à la vibration seule. Ces conclusions sont corroborées par les résultats de Menz et al. (2006). L'application d'un stimulus tactile sur la jambe des sujets a amélioré le contrôle postural chez une population variée (sujets jeunes, âgés ou pathologiques). L'effet était plus marqué lorsque le stimulus était placé au niveau du genou comparativement au placement au niveau de la cheville. L'utilisation de dispositifs de stimulation tactile variés permet notamment d'améliorer la perception de la position des segments corporels par un phénomène de résonance stochastique (Davids, 2004).

2.1.2. Phénomène de résonance stochastique

La stimulation tactile ne rend pas directement compte des mouvements corporels mais son application, notamment de faible intensité, va modifier le seuil des récepteurs pour les rendre plus sensibles aux mouvements du corps (Davids, 2004). Cette modification est décrite comme un phénomène de résonance stochastique (RS). Il s'agit d'une amélioration du fonctionnement des systèmes par l'ajout de bruit à des niveaux optimaux. La RS se base sur le phénomène de "bruit positif" pour améliorer le système sensorimoteur. Le bruit stochastique est omniprésent dans les systèmes biologiques, notamment neuronaux. Les neurones sont régis selon « la loi du tout ou rien », une réponse n'apparaît que si une intensité suffisante de stimulation est atteinte, c'est le seuil. Si le stimulus est insuffisant, le seuil n'est pas atteint et il n'y a pas de réponse de la cellule nerveuse. Si le stimulus est suffisant, le seuil est atteint et la réponse se produit. Cette réponse d'un neurone se propage sous la forme d'un potentiel d'action (Faisal et al., 2008). Ce phénomène ne se produit pas dans les systèmes linéaires, où l'ajout de bruit soit au système soit au stimulus ne fait que dégrader la détectabilité ou la qualité du signal (Moss, 2004; Ward et al., 2002). La résonance stochastique transforme un signal de sortie en une meilleure représentation du signal d'entrée lorsque du bruit est ajouté, par rapport au cas où il n'y a pas de bruit supplémentaire (Moss, 2004). La RS profite à la détection des signaux des récepteurs sensoriels afin d'améliorer la production motrice et à fortiori, le contrôle de l'équilibre. Avec un ajout de bruit approprié appliqué au signal sensoriel, les stimuli peuvent être détectés plus facilement, puisque les seuils d'activation des récepteurs sensoriels sont diminués, alors que sans l'ajout de bruit, les signaux externes demeurent indétectables. Le schéma de Davids (2003) illustre, plus explicitement, ce phénomène de résonance stochastique induit par le bruit (Figure 7).

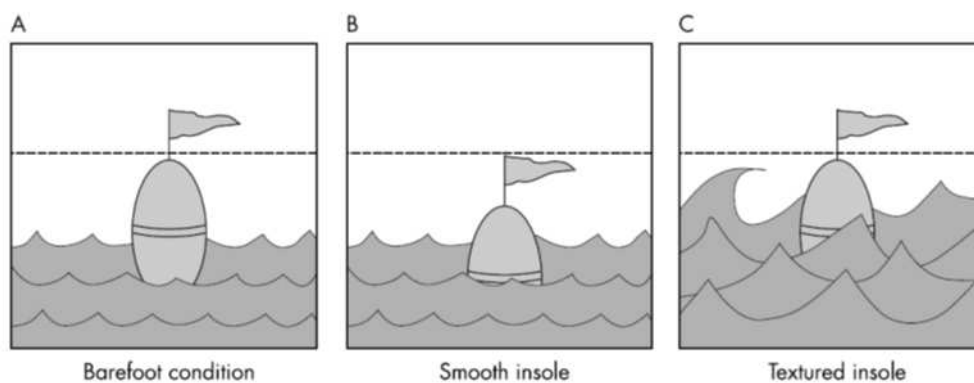


Figure 7 : Illustration de la résonance induite par le bruit (Davids, 2003)

Dans chaque figure, la bouée représente le signal (par exemple une afférence cutanée plantaire). Lorsque la bouée est sous la ligne, le stimulus ne peut pas être détecté par le participant, alors que lorsque le drapeau est au-dessus de la ligne, l'information sensorielle est détectable. Enfin, le liquide dans lequel la bouée est partiellement immergée représente le bruit de fond qui est toujours présent dans une certaine mesure dans les environnements naturels. Dans la condition pieds nus (A), le signal est clairement détectable car il n'y a pas d'effet d'amortissement lié au port de semelles souples comme avec une paire de chaussures de running classique. Il y a une petite quantité de bruit de fond qui a peu d'effet sur le rapport signal/bruit. Lorsque les participants portent des chaussures équipées de semelles amortissantes (B), le rapport signal/bruit diminue. Au contraire, le port d'une semelle texturée (C) induit du bruit dans le système, matérialisé par un liquide élevé. Le signal est alors renforcé par le bruit induit par la déformation des tissus dans les semelles texturées, créant l'effet de résonance. Dans ce cas, le bruit de fond supplémentaire est fonctionnel, ce qui ramène le système à des niveaux de perception similaires à ceux de l'état "pieds nus".

Le phénomène de RS est souvent évoqué dans la littérature pour expliquer les effets positifs que peuvent avoir des dispositifs exogènes sur le contrôle postural des sujets. La méta-analyse de Woo et al. (2017) précise que la RS induite par des stimulation électro-induites sub-sensorielles améliore le contrôle de l'équilibre dans 83.3% des études analysées. En effet, la majorité de ces études ont rapporté des améliorations significatives de la régulation posturale quel que soit le profil des participants : sujets souffrant d'arthrose (Collins et al., 2011), sujets âgés (Reeves et al., 2009) ou encore des adultes jeunes et en bonne santé (Moss, 2004). Keshner et al. (2014) ont également rapporté des effets positifs de la stimulation par RS vibratoire sur l'équilibre postural. L'ajout de bruit vibrotactile à la surface plantaire chez une population d'adultes en bonne santé a permis de diminuer l'amplitude des oscillations posturales. Dettmer

et al. (2015) et Priplata et al. (2002) ont également rapporté un effet bénéfique sur le contrôle de l'équilibre en ajoutant du bruit vibrotactile sur la sole plantaire, mais cet effet était plus marqué chez les adultes plus âgés que chez les jeunes. Les personnes qui présentent des oscillations posturales et une instabilité plus importante lors des essais de base bénéficiaient davantage de l'intervention que celles dont le contrôle postural était optimal (e.g. les adultes en bonne santé âgés de 18 à 35 ans) (Dettmer et al., 2015 ; Wu & Zhu 2007).

2.2. Différents dispositifs de stimulation tactile

2.2.1. *Orthèses et chaussures spécifiques*

Des dispositifs externes tels que les orthèses plantaires ou différents types de chaussures orthopédiques sont souvent mis en place pour améliorer le contrôle postural de sujets âgés et limiter le risque de chute (Hatton et al., 2013). L'amélioration du contrôle postural repose principalement sur l'étirement et la compression de la peau associée à une augmentation de la stimulation des afférences cutanées par le dispositif externe. Les sportifs qui souffrent d'instabilité chronique de la cheville portent souvent des orthèses pour s'entraîner ou jouer. Hadadi et al. (2011) ont montré que le port d'orthèses de chevilles pouvait réduire l'instabilité posturale du membre blessé. Le soutien mécanique au niveau de l'articulation de la cheville et l'augmentation des afférences cutanées peuvent expliquer cet effet positif des orthèses sur le contrôle postural. Smalley et al. (2018) ont testé l'effet d'un dispositif expérimental permettant d'imiter le retour somatosensoriel produit par les orthèses sans fournir de soutien mécanique au niveau de la cheville. Leurs résultats ont montré que ce dispositif permettait de réduire les oscillations posturales de la même façon qu'une orthèse traditionnelle. Cet effet était plus prononcé chez les participants dont la performance posturale initiale était la moins élevée. Des résultats similaires ont été rapportés par Pavaille et al. (2016) et Raffalt et al. (2019) avec des dispositifs relativement similaires.

2.2.2. *Semelles texturées*

Les semelles texturées sont des matériaux dont la texture permet de stimuler les afférences cutanées plantaires par une simple déformation à la surface de la peau (Orth et al., 2013). Différents types de semelles texturées peuvent être utilisées pour stimuler les afférences cutanées, comme des semelles à picots, à tubes, à rebords ou munies d'éléments vibrants. Les nodules qui recouvrent les semelles à picots peuvent améliorer le contrôle postural des personnes âgées souffrant de perte de sensibilité (Palluel et al., 2009, 2008; Qiu et al., 2012). Perry et al. (2008) et Woo et al. (2017) ont suggéré que le port de semelles texturées constituait une intervention simple pour lutter contre la perte de sensibilité cutanée plantaire et l'altération

du contrôle de l'équilibre liée à l'âge. Des améliorations du contrôle postural ont également été observées avec ce type de semelles chez des sujets jeunes et sains (Corbin et al., 2007; Orth et al., 2013). En stimulant les récepteurs cutanés plantaires, les semelles texturées permettent également de compenser la perte d'informations visuelles et de maintenir un contrôle postural efficace (Preszner-Domjan et al., 2012). Les semelles munies d'éléments vibrants ont également un impact bénéfique sur le contrôle postural de sujets jeunes et âgés, avec des effets plus importants chez les personnes âgées comparativement aux sujets jeunes (Hijmans et al., 2007; Priplata et al., 2002). Ces dispositifs induisant un phénomène de résonance stochastique peuvent également améliorer les déficiences du contrôle de l'équilibre liées à l'âge (Stephen et al., 2012).

2.2.3. Bandes compressives

Les bandes compressives de type « Kinesiotaping » (KT), développées par Kenzo Kase en 1970 avaient un usage thérapeutique. Leur utilisation s'est démocratisée lors des jeux olympiques de 2008 de Pékin. L'application de ces bandes adhésives élastiques à la surface de la peau semble entraîner une augmentation de la circulation sanguine et du flux lymphatique dans les parties du corps traitées (Williams et al., 2012). Les bandes de KT sont utilisées pour traiter différentes pathologies musculosquelettiques comme les entorses chroniques ou les maux de dos et peuvent potentiellement améliorer l'amplitude de mouvement, l'endurance musculaire et le contrôle moteur (Nelson, 2016). Plusieurs études comprenant des sujets blessés ont mis en exergue une amélioration de la proprioception suite à l'application de KT dans des tâches de repositionnement angulaire (Fereydonnia et al., 2019 ; Tamburella et al., 2014). Bishop et al. (2018) ont sélectionné 48 sujets souffrant de la rupture du ligament croisé antérieur (LCA) avec une perte de proprioception consécutive à la blessure. Des améliorations significatives de la proprioception ont été observées en disposant les bandes de KT au niveau du genou. Kim et al. (2018) ont rapporté des résultats similaires avec des sujets souffrant d'entorses de la cheville. L'utilisation de bandes de KT semble efficace dans la prévention et le traitement des entorses de la cheville, car elles améliorent le contrôle proprioceptif pendant la dorsiflexion et l'inversion (Seo et al. 2016 ; You et al., 2004). Hosp et al. (2018) ont rapporté des effets positifs sur la proprioception à l'application de KT respectivement sur les genoux d'une population âgée et au niveau des chevilles chez des sujets adultes. Globalement, les résultats montrent que ces effets semblent être plus marqués sur les sujets âgés et blessés (Bishop et al., 2018; Hosp et al., 2018; Williams et al., 2012).

2.3. Vêtements de compression

Depuis quelques années les vêtements de compression font l'objet d'un véritable engouement dans le monde sportif. Un grand nombre d'études scientifiques ont analysé les effets de ces vêtements sur l'expression des qualités neuromusculaires et la récupération (Born et al., 2013; Brown et al. 2017; Engel et al., 2016). L'impact des vêtements de compression sur le contrôle postural a été nettement moins étudié et les résultats ne permettent pas de faire émerger un réel consensus au regard de leur efficacité (Woo et al., 2017). Cette absence de consensus par rapport à un potentiel bénéfique des vêtements de compression sur le contrôle postural semble être liée à la diversité des sujets étudiés (jeunes, âgés, sains, blessés, sportifs).

2.4. Effets des vêtements de compression sur le contrôle postural en fonction de la typologie des sujets

2.4.1.1. Sujets sains et blessés

Peu d'études ont étudié les effets aigus des vêtements de compression sur le contrôle postural de sujets blessés malgré leur potentiel effet prophylactique. Les sujets blessés qui souffrent d'une rupture du LCA ont une asymétrie inter-membres marquée et sont, de ce fait, plus vulnérables aux lésions du membre inférieur (Mohammadi et al., 2012; Palm et al., 2012). Kuster et al. (1999) ont testé les effets du port de vêtements de compression chez des sujets récemment opérés du LCA. Les participants devaient réaliser un saut en contre bas d'une hauteur de 10 cm puis maintenir l'équilibre en position monopodal pendant 25 secondes. Les résultats ont mis en exergue que l'application de manchons de compression sur le membre opéré permettait de réduire les oscillations posturales tout en améliorant la coordination intermusculaire. Ces auteurs ont conclu à un effet prophylactique des manchons de compression, qui peuvent profiter aux sujets lors de la reprise de leurs activités. Les sujets sains ne semblent néanmoins pas bénéficier de ces effets positifs. En testant les effets de différents modèles de chaussettes de compression sur une population de 61 jeunes sujets sains actifs, Jaakkola et al. (2017) ont en effet montré qu'il n'y avait pas d'effets des chaussettes de compression sur les performances obtenues sur différents tests d'agilité et d'équilibre.

2.4.1.2. Sujets âgés

Les systèmes sensoriels (visuel, somatosensoriel et vestibulaire) et neuromusculaires ont inévitablement tendance à se détériorer avec l'âge. Des changements dans la sensibilité cutanée et des modifications de la morphologie des récepteurs sont en effet observés avec l'avancée en âge, ce qui expose les personnes âgées à un plus grand risque de chute (Paillard, 2016; Woo et al., 2021). Dans leur étude comparative, Hijmans et al. (2009) ont recruté 12 personnes âgées

en bonne santé (77-93 ans) et 15 jeunes adultes (19-24 ans) afin d'observer les effets aigus de la compression du pied et de la cheville sur la proprioception. Chez les jeunes adultes, la compression n'a eu aucun effet significatif sur la proprioception ou le contrôle de l'équilibre tandis que chez les personnes âgées, la compression de la cheville a été associée à une amélioration du positionnement de l'articulation. Cependant, une détérioration concomitante de leur équilibre a été observée. La compression du pied induite par la chaussette a probablement altéré la capacité des récepteurs cutanés plantaires à détecter de l'information (Woo et al., 2014). Récemment, Woo et al. (2021) ont testé différents niveaux de compression sur la proprioception chez 26 sujets âgés. Les résultats suggèrent que seul le port de chaussettes de compression (20-30 mmHg) a amélioré la précision de l'estimation du mouvement de flexion plantaire de l'articulation de la cheville. Le port de chaussettes de compression pourrait constituer une technique compensatoire pour atténuer les effets négatifs du vieillissement sur la proprioception (Woo et al., 2021, 2018).

2.4.1.3. Sujets sédentaires et sportifs

La pratique du sport améliore le contrôle postural des pratiquants (Paillard, 2017; Perrin et al., 2002). De plus, il apparaît évident que certains sports engendrent plus d'améliorations posturales que d'autres lorsque l'expression des habiletés motrices requises par le sport en question exige un niveau élevé d'habileté posturale. Les effets de l'activité physique et sportive sur le contrôle postural ont été évalués chez des pratiquants amateurs et des compétiteurs en comparaison avec des sujets témoins au moyen d'études transversales et expérimentales (Matsuda et al., 2008; Vuillerme et al., 2001). Selon ces auteurs, les sportifs experts présentent non seulement de meilleurs niveaux d'équilibration que les sujets témoins mais aussi que leurs homologues de niveaux inférieurs (Paillard, 2017). Hasan et al. (2016) ont analysés les effets des chaussettes de compression combinés à des semelles texturées sur la performance du coup de pied en football. Seule les athlètes « avancés » ont validé les critères de réussite de leurs frappes au pied. Il semblerait donc que les sujets experts soient plus à même d'exploiter les informations somatosensorielles fournies par les chaussettes de compression. Cet effet ne semble pas être réservé à un public élite. Ghai et al. (2018) ont en effet révélé que les vêtements compressifs appliqués sous le genou de 46 sportifs amateurs pouvaient améliorer la proprioception au niveau de cette articulation. Seules deux études traitent de l'effet des vêtements de compression sur le contrôle postural chez des sujets sportifs. Chez des skieurs alpins, Sperlich et al. (2013) n'ont pas montré de bénéfice significatif sur le contrôle postural associé au port de vêtements de compression. L'expérimentation de Michael et al. (2014) s'est

portée spécifiquement sur l'analyse du contrôle postural de 12 sportives. Les participantes devaient effectuer une tâche d'équilibre sur une seule jambe pendant 60 secondes sur une plateforme de force dans six conditions expérimentales, y compris les yeux ouverts et les yeux fermés, en portant un short classique (contrôle), un vêtement de compression ample et un vêtement de compression bien ajusté (sur la totalité du membre inférieur). Les mesures simultanées des forces de réaction au sol et de la cinématique des articulations du corps entier ont été enregistrées. Les auteurs concluent que la stabilité posturale lors du maintien en position monopodale a été améliorée par l'utilisation de vêtements de compression bien ajustés (dans la condition yeux fermés). Il semblerait que l'expertise puisse avoir un effet sur la capacité à tirer profit des informations somatosensorielles induites par le port de vêtements compressifs mais seule une étude en atteste.

Problématiques et objectifs

La somesthésie est un système ubiquitaire qui contribue fortement au contrôle de l'équilibre, il s'agit d'une véritable interface permettant les interactions entre le corps et son environnement. L'ensemble des sensations captées par le système somatosensoriel permet au SNC d'assurer la régulation posturale (Massion, 1994). En augmentant les informations apportées au système par une stimulation des mécanorécepteurs, il est probable que les vêtements de compression améliorent le contrôle postural. Cependant les effets des vêtements de compression sur le contrôle de l'équilibre n'ont pas clairement été établis. Certaines études ont montré que la compression n'avait pas d'effet bénéfique (Cavanaugh et al., 2016; Hijmans et al., 2009; Sperlich et al., 2013; Woo et al., 2014) tandis que d'autres soutiennent le contraire (Kuster et al., 1999; Michael et al., 2014; Palm et al., 2012; Woo et al., 2018). L'hétérogénéité de ces résultats pourrait provenir des caractéristiques des participants (e.g. âge, sexe, antécédents de blessure). Certaines études ont rapporté des résultats significatifs en faveur de la compression chez des sujets blessés en pré et post opération du ligament croisé antérieur (Kuster et al., 1999; Palm et al., 2012). Par ailleurs, si les résultats chez les sujets adultes et sains sont encore à discuter, les expérimentations sur les personnes âgées semblent montrer une amélioration du contrôle postural liée au port de vêtements de compression (Hijmans et al., 2009; Woo et al., 2018, 2017). Cette amélioration semble tributaire des conditions d'évaluation du contrôle de l'équilibre (e.g. tâches posturales statiques ou dynamiques, positions monopodales ou bipodales, les yeux ouverts ou fermés, sur un sol stable ou sur une surface instable). La majorité des résultats en faveur de la compression ont été obtenus lorsque les sujets se trouvaient dans une posture contraignante, en position monopodale les yeux fermés (Kuster et al., 1999; Michael et al., 2014; Palm et al., 2012; Woo et al., 2018). De plus, les propriétés des vêtements de compression utilisés (segments/articulations recouverts, niveau de compression) diffèrent entre les études. Chaque modèle comporte des pressions et des formes différentes qui n'influenceront pas de la même manière le contrôle postural (Woo et al. 2018).

Les études sur les dispositifs externes stimulant les mécanorécepteurs cutanés ont montré qu'il y avait une grande variabilité entre les réponses des individus (Pavailler et al., 2016; Rogers et al., 2001; You et al., 2004). De plus chaque individu peut potentiellement présenter des performances posturales différentes entre les deux jambes, responsable d'une asymétrie du contrôle postural (Paillard and Noé, 2020). Or la présence de ces asymétries peut nuire à la performance des sportifs et/ou entraîner des blessures (Bishop et al., 2018). Par conséquent, on

peut supposer que les effets des vêtements de compression sur le contrôle de l'équilibre seraient sujets à des variations selon le type de sujets recrutés.

Compte tenu des divergences dans la littérature concernant les vêtements compressifs, des effets positifs supposés sur la proprioception et du probable impact de la typologie des sujets sur les résultats, l'objectif principal de cette thèse était d'étudier l'effet des vêtements de compression sur le contrôle postural. Cet objectif principal est décliné en trois objectifs.

Le premier objectif était d'analyser les effets aigus du port des vêtements de compression sur le contrôle postural sur des sujets actifs en bonne santé.

Les effets du port des vêtements de compression semblent suivre une relation en forme de « U » selon la typologie des sujets. Cela signifie que les sujets présentant un contrôle postural déficient (e.g. sujets âgés ou blessés) ou au contraire très efficient (e.g. sportif de haut niveau) bénéficieraient davantage des informations cutanées supplémentaires apportées par le vêtement compressif que les sujets ordinaires, sains et actifs (Kuster et al., 1999; Michael et al., 2014; Palm et al., 2012; Woo et al., 2018). Sur la base de ce principe de la relation en forme de « U », les sujets sains en bonne santé ne tireraient pas profit du port de vêtements de compression pour améliorer leur contrôle postural (Cavanaugh et al., 2016; Hijmans et al., 2009; Jaakkola et al., 2017). Tous ces travaux ont cependant analysé les effets des vêtements de compression avec des approches statistiques standards sans s'intéresser à l'hétérogénéité des réponses individuelles (Cavanaugh et al., 2016; Hijmans et al., 2009; Jaakkola et al., 2017). Or, plusieurs études sur les effets de différentes modalités de stimulations tactiles (chaussures spécifiques, toucher digitale mécaniquement inefficace, orthèses) sur le contrôle postural de sujets jeunes et sains ont pu mettre en évidence une grande variabilité interindividuelle des réponses aux stimulations, liée notamment aux capacités proprioceptives intrinsèques des sujets (Pavailler et al., 2016; Rogers et al., 2001; You et al., 2004). On peut donc supposer que les effets des vêtements de compression sur le contrôle postural pourraient aussi varier au sein d'un échantillon de sujets jeunes et sains. Nous avons donc émis l'hypothèse que le port de vêtements de compression affectera différemment le contrôle postural des sujets issus d'une population d'adultes en bonne santé. Une analyse statistique originale (analyse en clusters) sera réalisée afin d'appréhender plus finement l'influence de la typologie des sujets dans les réponses induites par le port des vêtements de compression.

Le second objectif était d'analyser les effets aigus du port des vêtements de compression sur le contrôle postural d'athlètes de haut niveau.

Toujours sur la base de la relation en forme de « U », sachant que l'expertise sportive peut améliorer le processus de repondération sensorielle (Paillard, 2017), les athlètes de haut niveau sont susceptibles d'intégrer efficacement les informations cutanées générées par les vêtements de compression pour améliorer le contrôle de l'équilibre. A notre connaissance, seules deux études ont testé l'influence des vêtements de compression sur le contrôle postural chez les sportifs. Michael et al. (2014) ont montré que le port de tels dispositifs pouvait améliorer le contrôle postural tandis que Sperlich et al. (2013) n'ont signalé aucun effet bénéfique avec un groupe de skieurs alpins de haut niveau. Néanmoins, Sperlich et al. (2013) ont effectué un test d'équilibre avec des chaussures de ski. Ces chaussures, qui fournissent un soutien mécanique et stimulent les mécanorécepteurs cutanés du pied et de la jambe ont sans doute agit comme un facteur confondant ne permettant pas d'observer un potentiel effet positif liés aux vêtements de compression. Par conséquent, l'influence de l'expertise sportive sur la capacité à tirer parti des vêtements de compression pour améliorer le contrôle postural reste une question ouverte. Nous avons donc réalisé une étude afin d'examiner les effets du port des vêtements de compression sur le contrôle postural d'athlètes de haut niveau (joueurs de handball professionnels). Nous avons émis l'hypothèse que le port des vêtements de compression améliorerait le contrôle postural de ces sujets. En raison de l'hétérogénéité potentielle de la réponse des participants au port de vêtements compressifs, nous avons réalisé une analyse statistique en clusters afin d'identifier différents profils de réponses au port de vêtements de compression.

Le troisième objectif était d'analyser les effets aigus du port des vêtements de compression sur les asymétries de contrôle postural inter-membres.

La présence d'asymétries inter-membres peut avoir un impact négatif sur la performance sportive et est associée à une incidence élevée de blessures au niveau des membres inférieurs, en particulier si les asymétries concernent le contrôle postural (Bishop et al., 2018; Promsri et al., 2018; Stiffler et al., 2017). Les vêtements de compression peuvent améliorer le contrôle postural (Kuster et al., 1999; Michael et al., 2014; Woo et al., 2017) et la précision de mouvements complexes comportant une importante composante somatosensorielle (Broatch et al., 2021; Ghai et al., 2018; Hasan et al., 2016). La stimulation somatosensorielle associée au port de vêtements de compression peut donc potentiellement réduire les asymétries de contrôle postural entre les membres. Néanmoins, aucune étude n'a, à notre connaissance, spécifiquement étudié les effets du port des vêtements de compression sur les asymétries de contrôle postural inter-membres. Nous avons émis l'hypothèse que le port des vêtements de compression

réduirait les asymétries posturales inter-membres en particulier chez les sujets présentant un niveau d'asymétries élevé.

Techniques et méthodes :

Lors de nos expérimentations, l'évaluation du contrôle postural a été réalisée à partir d'une plateforme de force (Stabilotest Techno-Concept, Mane, France) équipée de capteurs de force permettant de quantifier la posture et l'équilibre des sujets par l'enregistrement des déplacements du centre des pressions avec une fréquence d'échantillonnage de 40Hz. Les sujets ont été invités à se placer debout les pieds nus (dans une posture standardisée) directement sur la plateforme et sur un plateau d'équilibre (Balance-board, Sissel® GmbH, Bad Dürkheim, Germany) apposé sur la plateforme. Il leur était demandé de bouger le moins possible. La plateforme de force produit une série temporelle bidimensionnelle représentant la trajectoire du centre des pressions (CP) dans les axes antéro-postérieur (AP) et médio-latéral (ML). La surface (S) et la vitesse moyenne du déplacement du CP sur les axes médio-latéral (VX) et antéro-postérieur (VY) ont été calculées à partir des données brutes du déplacement du CP. Ces paramètres linéaires très largement utilisés dans la littérature permettent de quantifier les oscillations posturales et de caractériser l'équilibre : plus les valeurs sont faibles plus le contrôle de l'équilibre est efficace (Paillard and Noé, 2015). Nous avons également calculé la sample entropie comme paramètre dynamique non linéaire. La sample entropie permet de quantifier la régularité ou la prévisibilité des séries temporelles du déplacement du centre des pressions (Lubetzky et al., 2018). Un processus régulier, donc plus prévisible, produit des valeurs d'entropie plus faibles qu'un processus moins régulier, plus imprévisible.

Des vêtements de compression type manchons portés au niveau de la jambe (Booster, BV sport®, Saint Etienne, France) composés de 79% de polyamide et de 21% d'élasthanne ont été utilisés. Ces manchons ont la caractéristique d'avoir une compression progressive. Cela se caractérise par une pression qui augmente progressivement de 13 mmHg à la partie inférieure du mollet à 20-25 mmHg au niveau des gastrocnémiens (20 mmHg à la partie latérale et 25 mmHg à la partie médiale). La taille des manchons de compression a été adaptée individuellement selon les directives des fabricants, en fonction de la taille et de la circonférence du mollet des participants. Quatre tailles ont été utilisées : M+, L+, XL+ et XXL+, dimensionnées pour 34-38/>175, 38-43/>175, 38-43/>192, 43-48/192 (tour de mollet/taille, en cm), respectivement, de manière à s'adapter à la morphologie de tous les participants.

Partie II - Etudes expérimentales

1. Article 1

**Effects of Compression Garments on Balance Control in Young
Healthy Active Subjects: A Hierarchical Cluster Analysis**

Kévin Baige, Frédéric Noé, Noëlle Bru and Thierry Paillard

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1.1. Abstract

There is controversy about the influence of compression garments on balance control. A positive influence was reported in elderly and injured individuals, whereas no beneficial effects were observed in young healthy active subjects, which is likely due to the large inter-individual differences in these subjects. Hence, this study investigated the acute effects of compression garments on balance control in young healthy active subjects by addressing the issue of heterogeneity of individuals' responses to the wearing of compression garments. Thirteen young, healthy, active subjects were recruited. They stood on a force plate which recorded the center of foot pressure displacements in a monopodal stance with the eyes closed and on a wobble board with the eyes open, while wearing compression garments or not. Statistics were first calculated with the data from the whole sample. A hierarchical cluster analysis was also performed in order to categorize the participants' behaviors into subgroups with similar characteristics. The whole group analysis showed that there were no significant effects attributed to compression garments. The clustering analysis identified distinct and homogeneous subgroups of participants. Only participants who swayed the more at baseline benefited from the wearing of compression garments to improve their balance control. These participants might have either a gravity-dependent preferred sensorimotor strategy with an exploratory postural behavior or poorer balance/proprioceptive abilities. Since poor balance control is a predictor of sports injury risk, wearing compression garments during sports practice could be viewed as a potential prevention strategy for individuals at risk.

Keywords: sports, posture, postural balance, sensorimotor control, sensory reweighting

1.2. Introduction

The somatosensory system highly contributes to balance control. It provides information about body movements that lead to small-sized tissue deformation and activation of cutaneous, muscle, and articular mechanoreceptors (Krishnamoorthy et al., 2002). From an ecological perspective (Gibson, 1966), the somatosensory system should not be reduced to the mere consideration of nerve cells (i.e., mechanoreceptors): it should be considered at a more expansive scale while integrating nerve, muscle, and connective tissue cells in a complex tensegrity assemblage (Palatinus et al., 2014; Turvey and Fonseca, 2014). Connective tissue is of particular importance since it has a uniting function by binding every cell to its neighbors in order to form a whole medium that enables the transmission and the distribution of mechanical forces within the tensegrity assemblage (Palatinus et al., 2014; Turvey and Fonseca, 2014). Such a unification gives emphasis of relations between individual cells, which facilitate the pickup of information about body motion that emerges from interactions between perception, action, information, and task goal (Riley et al., 1999). In this context, the wearing of compression garments may change the tension–compression relations in the tensegrity assemblage. Actually, the overall constriction provided by compression garments acts as a mechanically supportive framework sensitive to body movements that can activate interacting cutaneous mechanoreceptors that individually would not have been activated. Hence, compression garments can enhance the perception of somatosensory information and influence balance control positively by reducing body sway during quiet standing (Kuster et al., 1999; Michael et al., 2014; Woo et al., 2018, 2017). These beneficial effects of compression garments on balance control would be most pronounced among elderly and injured subjects (Kuster et al., 1999; Palm et al., 2012; Woo et al., 2018; You et al., 2004) and high-level athletes (Michael et al., 2014). These results suggest that only subjects with either sensory deficits, such as elderly and injured subjects, or exceptional sensory acuity and/or sensory reweighting mechanisms, such as high-level athletes (Paillard, 2019, 2017), would be able to benefit from compression garments to improve balance control. By comparison, “ordinary” active subjects such as young, healthy, non-injured subjects and non-elite/recreational athletes would not benefit from compression garments to improve balance control (Cavanaugh et al., 2016; Hijmans et al., 2009; Jaakkola et al., 2017). Further studies about the influence of external devices that stimulate cutaneous receptors have shown that there was a great variability between individuals’ responses to cutaneous stimulation (Pavaiier et al., 2016; Rogers et al., 2001; You et al., 2004). Hence, one can assume that the effects of compression garments on balance control would be subject-dependent in active subjects. This could explain the absence of a significant effect as

reported by studies about the influence of compression garments on balance control in active subjects (Cavanaugh et al., 2016; Hijmans et al., 2009; Jaakkola et al., 2017). Actually, these studies were performed with standard group ensemble average statistical approaches that do not allow to specifically address the issue of heterogeneity of individuals' postural behavior to the wearing of compression garments. The purpose of this study was therefore to investigate the effects of compression garments on balance control in young, healthy, active subjects by addressing the issue of inter-individual variability in the ability to take advantage of compression garments to improve balance control. To this end, a hierarchical cluster analysis was performed. The clustering analysis is a multivariate statistical method which categorizes the participants' behaviors into subgroups with similar characteristics, thus facilitating the investigation of differences in individual responses by enabling the identification of natural groupings that may exist in a whole sample (Watelain et al., 2000; White and McNair, 2002). It was hypothesized that the wearing of compression garments differently affected balance control in active subjects.

1.3. Materials and Methods

Participants

Thirteen male young, healthy, active subjects having recreational handball practice (age: 27.9 ± 8.36 years old, height: 178.6 ± 7.89 cm; body mass: 79.62 ± 14.28 kg; training hour per week: 3 h; mean \pm SD) participated voluntarily in the experiment. The exclusion criteria included any neuromuscular impairments and/or ankle, knee, and hip trauma in the past 2 years and medication that might influence balance. The participants were also asked to avoid strenuous activity and the ingestion of alcohol or/and excitatory substances 24 h before the experimental session. All the participants voluntarily signed an informed consent before starting the experiment, which was in accordance with the Declaration of Helsinki. All procedures were approved by and performed in accordance with the relevant guidelines and regulations of the University of Pau and Adour Countries Ethics Committee.

Apparatus and Procedure

The participants were asked to sway and move as little as possible when standing barefoot in a monopodal stance on their nondominant leg (i.e., the supporting leg, which was determined as the leg which is not used to kick a ball) for 25 s on a force platform (Stabilotest R Techno ConceptTM, Mane, France) which sampled the center of foot pressure displacements at 40 Hz. Two postural tasks were conducted in a counterbalanced order: a stable task where the

participants stood on stable ground with the eyes closed (while keeping their gaze straight ahead) and an unstable task where they stood on a wobble board with a diameter of 40 cm and a height of 8 cm (Balance-board, Sissel R GmbH, Bad Dürkheim, Germany) with the eyes open (while looking at a fixed-level target at a distance of 2 m). These postural tasks were chosen because tactile cues provided by a light touch or by garments that stimulate cutaneous receptors are more effective in conditions of increased sway, i.e., when standing on an unstable surface and/or when a sensory pathway critical for standing posture is perturbed (e.g., when vision is occluded) (Michael et al., 2014; Rogers et al., 2001; Woo et al., 2018). For accurate and similar feet positioning between all subjects, the foot was placed according to precise landmarks on the force platform and the wobble board. All postural tasks were performed with or without wearing compression garments (COMP and REF condition respectively). In the COMP condition, calf compression sleeves (Booster, BV sport R, Saint Etienne, France) made of 69% polyamide, 21% elastane, and 10% yarn were worn by the participants. The pressure was 0 mmHg at the ankle, 20 mmHg at the external spinning, and 25 mmHg at the internal spinning of the calf. In order to avoid any learning effect, the participants had to perform a familiarization session before data acquisition while performing two trials in each postural task (Cug et al., 2014). Center of pressure (COP) surface area (S: 90% confidence ellipse), mean center of pressure velocity along the medio-lateral (VX), and antero-posterior (VY) axes were calculated as linear measures characterizing balance control and postural sway; within the framework of a quiet stance paradigm, the lower these parameters, the lower amount of postural sway and the more efficient the balance control (Paillard and Noé, 2015). The analysis of the dynamical features of postural sway variations was calculated from the sample entropy (SampEn). Sample entropy was calculated from the resultant COP velocity using the method proposed by (Ramdani et al., 2009), with $m = 3$ and $r = 0.2$. SampEn provides information about the regulation processes involved in balance control and attention investment. Low SampEn values characterize repetitive patterns of sway movements and reflect a strong cognitive contribution to balance control with reduced adaptive abilities. High SampEn values are indicative of a more automatic and adaptive control of balance (Ramdani et al., 2009; Vaillancourt and Newell, 2002). The relative difference of each center of pressure parameter between both conditions [relative difference = $100 \times (\text{COMP} - \text{REF})/\text{REF}$] was also calculated. Relative difference is an easily interpretable descriptor, which limits the influence of the heterogeneity between participants in the REF condition and makes it easy to differentiate participants who benefit from CG wearing (negative value of relative difference of linear center of pressure metrics and positive value of

relative difference of SampEn) and those who do not (positive value of relative difference of linear center of pressure metrics and negative value of relative difference of SampEn).

1.4. Statistical analysis

Data were analyzed in two steps. The first step consisted of analyzing the influence of experimental conditions (REF and COMP) on dependent variables (S, VX, VY and SampEn) with a standard group ensemble average method (whole group analysis). Normality was tested using Shapiro–Wilk test. As the dependent variables did not meet the assumption of normal distribution, non-parametric Wilcoxon signed-rank tests were applied to determine differences between the REF and the COMP conditions in terms of the relevant dependent variable. A hierarchical cluster analysis was performed in a second step to classify the participants' behavior into subgroups with similar characteristics (Watelain et al., 2000; White and McNair, 2002). A normalized principal component analysis was first used to reduce the dimensionality of the data prior to performing the hierarchical cluster analysis based on the five first principal component scores. COP parameters in the REF condition (S, VX, VY, and SampEn) and the relative differences (RD) of each COP parameter (RD_S, RD_VX, RD_VY, and RD_SampEn) between both conditions were used to produce a 13×8 input matrix for the PCA [13 (number of participants) \times 8 (input variables)]. Once the number of clusters was identified, univariate tests were performed on dependent variables to determine which parameters best determine the cluster placement due to a significant difference from whole group mean (Lê et al., 2008). The stable and the unstable postural tasks were analyzed independently as two separated datasets. Statistical analyses were performed with R statistical software using FactoMineR Package (Lê et al., 2008). The significance level was set at $p < 0.05$.

1.5. Results

Table 1 illustrates the mean values of the center of pressure parameters in the whole sample with the characteristics of each cluster. When inferential statistics were conducted on the whole group, no significant differences were observed between REF and COMP conditions in both the stable and the unstable postural tasks. In the stable postural task, the principal component analysis resulted in two components that explained 68.5% of the total variance of the original dataset. The first principal component accounted for 48.2% of the total variance. Among the variables that loaded this component, S_REF, VX_REF, and VY_REF were positively correlated, whereas RD_S and RD_VY were negatively correlated (**Figure 1A**). The second principal component explained 20.3% of the total variance and was mainly loaded with two variables, RD_VY and RD_SampEn, that were positively correlated. **Figure 1B** illustrates the

individuals' factor map with the results from the hierarchical cluster analysis. Two clusters were identified with a heterogeneous distribution of individuals among the clusters (cluster 1, n = 10; cluster 2, n = 3). The center of pressure parameters that best determined group placement was acting on the first principal component axis (S_REF, VX_REF, VY_REF, RD_S, and RD_VY). Individuals from cluster 1 had low values of linear center of pressure metrics in the REF condition (S_REF, VX_REF, and VY_REF) and positive values of relative difference between both conditions (RD_S and RD_VY). Individuals from cluster 2 had high values of linear center of pressure metrics in the REF condition and negative values of relative difference. In the unstable postural task, we left out participant number 7 from the analysis. As illustrated in **Figure 2B**, he was identified as an outlier on several dependent variables of the initial dataset (VY_REF, S_REF), which influenced the construction of the space too significantly. Participant number 7 was entered as an illustrative individual, and 12 active individuals were included in the principal component analysis and cluster analyses. The principal component analysis resulted in two components that explained 60.6% of the total variance of the original dataset. The first principal component accounted for 36.2% of the total variance and was mainly loaded with four variables: RD_S and RD_VY that were positively correlated and VX_REF and VY_REF which were acting in the opposite direction. The second principal component explained 24.3% of the total variance and was mainly loaded with five variables: RD_S, RD_VX, VY_REF, and SampEn REF that were positively correlated and RD_SampEn which was acting in the opposite direction (**Figure 2A**). Three clusters were identified with a fairly homogeneous distribution of individuals among the clusters (cluster 1, n = 4; cluster 2, n = 3, cluster 3, n = 5). The COP parameters that best determined group placement were acting on the PC1 axis (S_REF, VX_REF, VY_REF, RD_S, and RD_VY). Individuals from cluster 1 differed from the whole group by having higher values of VX_REF and lower values of RD_VX and RD_VY. Individuals from cluster 2 had higher values of SampEn_REF and RD_VX than those of the whole group. Finally, individuals from cluster 3 had lower values of SampEn_REF and VY_REF than those of the whole group (**Figure 2C** and **Table 1**).

			<i>n</i>	REF	COMP	RD (%)
Stable task	S (mm ²)	Whole group	13	2,007.48 (1,120.31)	1,865.7 (801.08)	8.04 (43.41)
		Cluster 1	10	1,506.21 (580.01) ^a	1,807.212 (815.42)	22.67 (35.66) ^a
		Cluster 2	3	3,678.40 (756.58) ^a	2,060.50 (885.60)	-40.75 (30.72) ^a
	VX (mm s ⁻¹)	Whole group	13	65.07 (16.61)	64.55 (18.07)	-0.13 (14.54)
		Cluster 1	10	57.96 (10.25) ^a	58.3 (12.87)	1.11 (14.73)
		Cluster 2	3	88.76 (9.32) ^a	85.38 (19.17)	-4.28 (16.09)
	VY (mm s ⁻¹)	Whole group	13	52.51 (18.5)	51.73 (16.99)	3.70 (32.27)
		Cluster 1	10	43.52 (7.58) ^a	49.74 (17.77)	13.71 (29.33) ^a
		Cluster 2	3	82.47 (6.51) ^a	58.37 (14.99)	-29.68 (14.37) ^a
	SampEn	Whole group	13	1.26 (0.18)	1.26 (0.22)	0.37 (12.04)
		Cluster 1	10	1.24 (0.19)	1.23 (0.23)	-0.56 (13.73)
		Cluster 2	3	1.31 (0.20)	1.35 (0.16)	4.00 (4.81)
Unstable task	S (mm ²)	Whole group	13	700.55 (384.28)	693.70 (266.23)	6.96 (29.87)
		Cluster 1	4	619.50 (101.37)	538.83 (95.28)	-13.02 (8.03) ^a
		Cluster 2	3	679.70 (344.44)	874.23 (375.62)	32.30 (24.16)
		Cluster 3	5	558.74 (209.10)	608.32 (118.46)	15.77 (30.88)
	VX (mm s ⁻¹)	Whole group	13	41.04 (11.70)	39.15 (8.53)	-0.75 (23.71)
		Cluster 1	4	47.38 (6.43) ^a	38.53 (3.87)	-18.24 (5.97) ^a
		Cluster 2	3	34.95 (8.72)	44.79 (14.95)	26.60 (13.41) ^a
		Cluster 3	5	33.90 (2.15)	34.94 (6.17)	3.54 (19.96)
	VY (mm s ⁻¹)	Whole group	13	26.83 (8.49)	26.34 (5.68)	1.01 (12.73)
		Cluster 1	4	28.93 (4.39)	26.63 (2.6)	-7.14 (10.50) ^a
		Cluster 2	3	29.40 (5.48)	30.13 (4.19)	3.16 (5.76)
		Cluster 3	5	19.46 (1.70) ^a	21.51 (2.97)	10.42 (9.86)
	SampEn	Whole group	13	1.34 (0.22)	1.39 (0.18)	4.71 (9.93)
		Cluster 1	4	1.34 (0.10)	1.37 (0.17)	2.52 (9.3)
		Cluster 2	3	1.59 (0.24) ^a	1.56 (0.15)	-1.04 (10.07)
		Cluster 3	5	1.17 (0.14) ^a	1.30 (0.19)	11.01 (9.62)

Table 1. Center of pressure (COP) parameters of the whole group with cluster characteristics in the different postural tasks and experimental conditions.

Data are expressed as mean (SD). S, COP surface area; VX and VY, mean COP velocity along the medio-lateral and antero-posterior axes, respectively; SampEn, sample entropy; *n*, frequencies for the whole group and subgroups; REF, reference condition; COMP, compression garments condition; RD, relative difference between both conditions [RD = 100 × (COMP – REF)/REF].

^a Variable identified as determinant of cluster placement due to a significant difference from the whole group mean (*p* < 0.05).

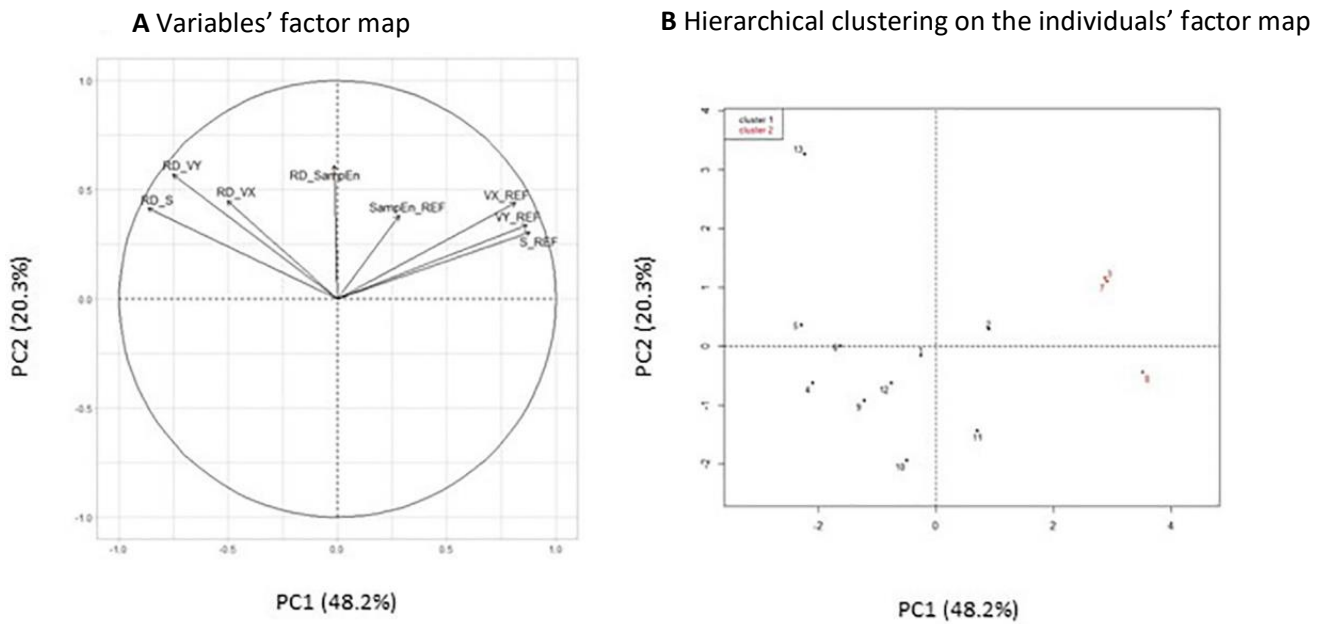


Figure 1. Variables' factor map (A) of the principal component analysis applied on center of pressure (COP) parameters in the stable postural task and hierarchical clustering on the factor map (B). Individuals from clusters 1 and 2 are represented by black and red dots, respectively. S_REF , COP surface area in the REF condition; VX_REF , mean COP velocity along the medio-lateral axis in the REF condition; VY_REF , mean COP velocity along the antero-posterior axis in the REF condition; RD_S , RD_VX , RD_VY , and RD_SampEn , relative difference between both conditions [$RD = 100 \times (COMP - REF)/REF$] of S , VX , VY , and $SampEn$ variables.

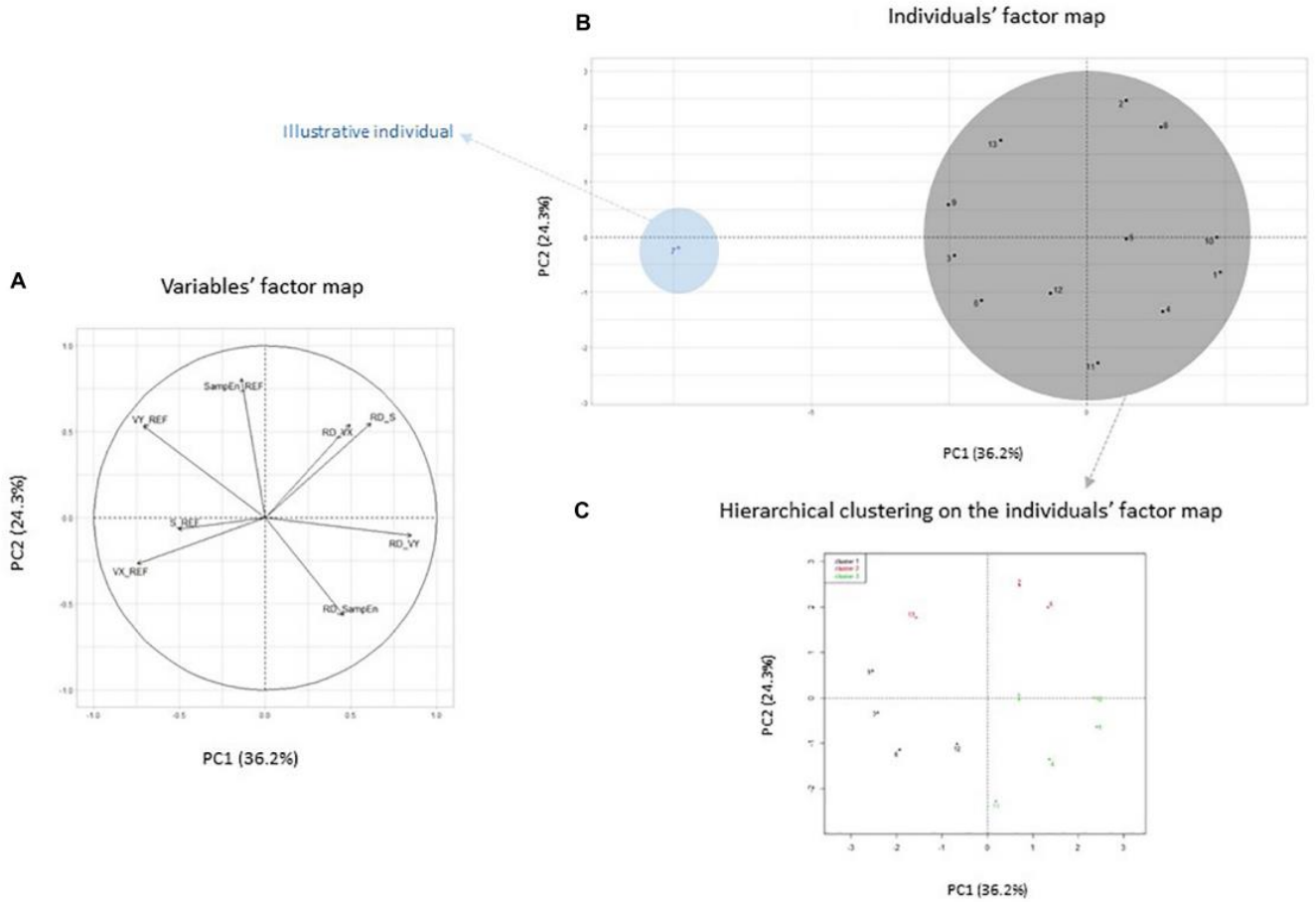


Figure 2. Variables' factor map and individuals' factor map (A, B) of the principal component analysis applied on center of pressure (COP) parameters in the unstable postural task and hierarchical clustering on the factor map (C). Individuals from clusters 1 and 2 are represented by black and red dots, respectively. *S_REF*, COP surface area in the REF condition; *VX_REF*, mean COP velocity along the medio-lateral axis in the REF condition; *VY_REF*: mean COP velocity along the antero-posterior axis in the REF condition; *SampEn_REF*; *RD_S*, *RD_VX*, *RD_VY*, and *RD_SampEn*, relative difference between both conditions [$COMP = 100 \times (CG - REF)/REF$] of *S*, *VX*, *VY*, and *SampEn* variables.

1.6. Discussion

The aim was to determine whether wearing of compression garments results in high variability between individuals' responses among a group of young, healthy, active subjects. The cluster analysis identified further distinct subgroups within the whole group of participants in each postural task, thus highlighting a large variation of individuals' responses to the wearing of compression garments. In both postural tasks, only individuals who exhibited the highest values of linear center of pressure parameters in the REF condition (i.e., the less efficient or the more exploratory balance control at baseline) benefited from the wearing of compression garments to improve their balance control. When statistics were performed on the whole group, our results showed that the wearing of compression garments did not significantly impact balance control. Previous studies about the effects of garments that interact with skin mechanoreceptors, such as compression garments, ankle braces, and taping, have also produced concordant findings with young, healthy, non-injured subjects and recreational sports people (Cavanaugh et al., 2016; Inglés et al., 2019; Jaakkola et al., 2017; Medeiros Barbosa et al., 2019; Papadopoulos et al., 2007; Willeford et al., 2018). Nevertheless, the clustering approach identified distinct subgroups of participants who responded differently to the wearing of compression garments. This result is consistent with some studies about the influence of external devices that stimulate skin mechanoreceptors on balance control, which have reported a high inter-individual variability in responses to cutaneous stimulation within a homogeneous group of young, healthy participants (Pavailler et al., 2016; Rogers et al., 2001; You et al., 2004). In both the stable and the unstable postural tasks, the clusters were differentiated according to the participants' balance behavior at baseline and their ability to benefit—or not—from CG wearing to improve balance control. The participants who exhibited an efficient balance control at baseline, with low linear metrics of postural sway and/or high values of sample entropy at baseline (participants from cluster 1 in the stable task and from clusters 2 and 3 in the unstable postural task), did not take advantage from compression garments to improve their balance control. Only the participants who exhibited higher linear metrics of postural sway at baseline (participants from clusters 2 and 1 in the stable and the unstable postural task, respectively) benefited from the wearing of compression garments (illustrated by negative values of relative differences of linear center of pressure parameters between COMP and REF condition) to improve their balance control. (Rogers et al., 2001) reported concordant findings while showing that the application of tactile stimuli benefited, to a larger extent, the subjects who swayed more during normal standing. These authors hypothesized that the subjects who swayed the most at baseline might present a moderate sensorimotor deficit, thus explaining why

the addition of tactile stimuli led to a greater reduction in sway. (Woo et al., 2017) formulated a similar hypothesis while postulating that the subjects with healthy postural control systems may not benefit from garments that interact with cutaneous receptors to enhance balance control. Further studies about the influence of external devices that stimulate cutaneous receptors (e.g., CG, ankle brace, and elastic bandages) on leg proprioception reported concordant findings when showing that the magnitude of the beneficial effects of cutaneous stimulation was inversely related to the participant's proprioceptive acuity at baseline (Cameron et al., 2008; Perlau et al., 1995; You et al., 2004). (You et al., 2004) also showed that external skin stimulation improved balance control only in subjects with low proprioceptive acuity. In the present study, we could therefore logically assert that the subjects who swayed the most benefited from the wearing of compression garments to improve their balance control because of a poorer balance control at baseline due to poorer lower limb proprioception. Nevertheless, (Pavallier et al., 2016) suggested that the ability to benefit from cutaneous stimulation provided by external supports was not only related to proprioceptive acuity but also to differences in how individuals weigh somatosensory cues for controlling their balance (i.e., differences in the preferred sensorimotor strategy). According to these authors, cutaneous stimulation would be of greater benefit to the subjects who rely more on gravito-inertial cues (gravity-dependent subjects) than on proprioceptive cues (support-dependent subjects). It is known that gravity-dependent subjects adopt an exploratory postural behavior while exhibiting larger postural sway to gain information from graviceptive signals (e.g., vestibular cues) more efficiently (Isableu and Vuillerme, 2006; Pavallier et al., 2016). Even though the subjects in the present study were asked to sway as little as possible in the context of a quiet stance paradigm, those who exhibited a greater postural sway could have a more exploratory postural behavior associated with a gravity-dependent sensorimotor strategy. However, exploratory movements have causal effects on the accuracy of affordance judgments (Stoffregen, 2003; Yu et al., 2011). Within the ecological approach to perception and action, the contents of perception are affordances (Gibson, 1966; Stoffregen, 2003). Affordances are neither properties of a subject nor properties of their environment, but they are emergent properties of the subject–environment system (Stoffregen, 2003). Compression garments act as a mechanically supportive framework which has a uniting function by nesting constricted mechanoreceptors, thus offering the opportunity to facilitate the pickup of information about sway-related movements in order to comply with the steadiness instruction. Compression garments did not enhance somatosensory perception per se, and one should rather consider a subject wearing compression garments as a system that provides an affordance for reducing postural sway. Stoffregen (2003) stated that affordances

are “what one can do, not what one must do,” which means that affordances are opportunities that are not necessarily exploited by subjects (Riley et al., 1999). Actually, the exploitation of affordances is intimately linked to the availability of body movements (Stoffregen, 2003). An affordance can be viewed as a hidden property of a system that would become meaningful when the system is subjected to movement. (Yu et al., 2011) showed, for example, that a certain amount of body sway was necessary for the perception of affordances. In the present study, the accuracy of affordance perception might have been higher in the participants who swayed more at baseline, those who have a typical profile of support-dependent subjects. With a greater sway, greater interactions certainly occurred between the cutaneous mechanoreceptors located under the compression garments, thus facilitating the pickup of information about sway-related movements. This could explain why only these subjects were able to take advantage from compression garments to reduce their postural sway. This study showed that, among a sample of young, healthy, active subjects, only the participants who exhibited the higher amount of postural sway could benefit from the wearing of compression garments to comply with the steadiness instruction. Hence, it can be suggested that the ability to take advantage from the wearing of compression garments to improve balance control depends on the subjects’ balance/proprioceptive abilities at baseline or preferred sensorimotor strategy. Further experiments are needed to explore how preferred sensorimotor strategy and balance/proprioceptive abilities influence the ability to take advantage of compression garments to improve balance control. From a practical point of view, knowing that poor balance control is a predictor of sports injury risk (Hrysomallis, 2011), subjects at higher risk of injury are likely to benefit from the wearing of compression garments. Hence, wearing compression garments during sports practice could be viewed as a cost-effective injury prevention strategy that would have a specific impact on individuals at risk without having any deleterious effects on other individuals.

2. Article 2

Wearing compression garments differently affects monopodal postural balance in high-level athletes

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2.1. Abstract

This study investigated the acute effects of compression garments (CG) on balance control in elite athletes. 15 male professional handball players were recruited. They had to stand as motionless as possible in a monopodal stance on a force plate with the eyes closed and on a wobble board with the eyes open, while wearing CG or not. Centre of foot pressure mean velocity and surface area were calculated. Statistics were first calculated with the data from the whole sample. A hierarchical cluster analysis was also performed in order to categorize the participants' behaviours into subgroups with similar characteristics. The whole group analysis showed that there were no significant effects attributed to CG. The clustering analysis identified two distinct and homogeneous subgroups of participants. Only athletes with the best balance abilities at baseline could benefit from CG wearing to improve their balance control. These athletes, who swayed less and were more sensitive to somatosensory manipulation due to CG wearing, seem to control balance by adopting a support-dependent preferred sensorimotor tactic. Our findings suggest that amongst high-level athletes, the ability to benefit from CG wearing to improve balance control seems to depend on participants' intrinsic balance skills and/or preferred sensorimotor tactics.

2.2. Introduction

Compression garments (CG) have been widely used in medicine in patients with venous disease, restricted mobility or with an immobilization of the lower limb for many years (Lattimer et al., 2013). CG create an external pressure gradient on the body surface which improves venous hemodynamics and prevents leg swelling and blood clots (Dermont et al., 2015; Lattimer et al., 2013). The wearing of CG in sport has also become very popular during and after training or competition in order to improve physical performances (Beliard et al., 2015; Engel et al., 2016) and to accelerate recovery (Brown et al., 2017; Hill et al., 2014). Suggested mechanisms include attenuation of muscle oscillation during exercise (Born et al., 2013; Engel et al., 2016), enhanced venous return, blood flow and muscle oxygenation with accelerated metabolic removal (Dermont et al., 2015; Ménétrier et al., 2013), reduced post-exercise edema (Partsch et al., 2004) and attenuated markers of muscle damage (Brown et al., 2017). CG could have a beneficial influence on endurance exercise mainly by attenuating perceived exertion and muscle soreness and by improving running economy (Born et al., 2013; Engel et al., 2016). CG could also affect neuromuscular performances such as vertical jumping and sprint performance. The exact mechanisms by which CG impact neuromuscular performances are not clear, but it may be due to the activation of cutaneous mechanoreceptors which elicits enhancements in the ability to perceive position in space and improves accuracy of motor actions such as jumping technique (Born et al., 2013; Doan et al., 2003; Loturco et al., 2016). The additional sensory cues from cutaneous mechanoreceptors provided by CG are also likely to improve movement control such as balance control (Espeit et al., 2017; Kuster et al., 1999). When specifically focusing on the influence of CG on balance control, studies showed that CG did not bring any beneficial effect (Cavanaugh et al., 2016; Papadopoulos et al., 2007), whereas others showed that balance control was enhanced when wearing CG (Kuster et al., 1999; Michael et al., 2014; Palm et al., 2012; Woo et al., 2018; You et al., 2004). The heterogeneity in these results might stem from participants characteristics (e.g., age, sex, healthy vs injured), conditions of balance control assessment (e.g. static vs dynamic postural tasks, monopodal vs bipodal stances, with eyes open or closed, on stable ground or unstable/compliant surface) and CG properties (segments/joints covered by the CG, level of compression). In general, CG rather induce beneficial effects when standing in monopodal stance (Kuster et al. 1999; Michael et al. 2014; Palm et al. 2012; You et al. 2004) especially with the eyes closed (Kuster et al., 1999; Michael et al., 2014; Palm et al., 2012). Only (Woo et al., 2018) reported a positive influence of CG with a bipedal stance when assessing elderly participants who had to perform a Romberg test on a compliant surface. CG seem to

preferentially benefit to subjects with lower limb injuries (Kuster et al., 1999; Michael et al., 2014; Palm et al., 2012) than to non-injured subjects (Cavanaugh et al., 2016; Jaakkola et al., 2017). The location of the compression (i.e. ankle, shank, knee or thigh) does not seem to be a major factor in explaining the differences observed in the studies. Some studies reported beneficial effects of CG on balance control with knee sleeves (Kuster et al., 1999; Palm et al., 2012), socks (Woo et al., 2018) and leggings (Michael et al., 2014) whereas others did not report any beneficial effect with knee sleeves (Cavanaugh et al., 2016) and socks (Hijmans et al., 2009; Jaakkola et al., 2017; Sperlich et al., 2013). Similarly, the level of compression, which is not systematically specified in the studies, does not appear to be a major factor in explaining the heterogeneity of the results. Studies that have tested the effects of wearing CG of different compression levels reported that the level of compression had no influence on balance control (Sperlich et al., 2013; Woo et al., 2018, 2017). Overall, CG would rather improve balance control in physically diminished/impaired subjects (e.g., elderly and injured) than in healthy young ones in particular in monopodal stance. Nonetheless, knowing that expertise in sport can enhance the process of sensory reweighting (Paillard, 2017), expert athletes are likely to integrate more efficiently the cutaneous stimulation provided by CG to improve balance control. Only two studies, to our knowledge, have been conducted in order to test the influence of CG on balance control in sportspeople, while producing divergent findings (Michael et al., 2014; Sperlich et al., 2013). (Michael et al., 2014) showed that balance control of sportswomen was improved when they wore CG, whereas (Sperlich et al., 2013) did not report any beneficial influence of CG in a group of competitive alpine skiers. Nevertheless, (Sperlich et al., 2013) performed a balance test with and without CG while asking participants to wear racing ski-boots. These boots, which stimulate cutaneous mechanoreceptors in the foot and shank and provide a mechanically efficient support at the tibia level (Noé et al., 2020), might have acted as a confounding factor and hid a potential positive effect of CG. Hence the influence of expertise in sport on the ability to take advantage for CG to improve balance control remains an open question. Consequently, this study was undertaken in order to investigate the acute effects of calf compression sleeves on monopodal balance control of professional elite handball players. It was hypothesized that calf compression sleeves would enhance monopodal balance control in professional handball players. Because of potential heterogeneity between participants' response to CG wearing, a normalized principal component analysis was used to reduce the dimensionality of the data before performing a hierarchical cluster analysis (HCA). The HCA is a multivariate statistical method which categorizes the participants' behaviours into subgroups with similar characteristics, thus facilitating the investigation of differences in

individual responses by enabling the identification of natural groupings that may exist in a whole sample (Watelain et al., 2000; White and McNair, 2002).

2.3. Materials and Methods

Methods Participants. Fifteen male handball players from the same team in the professional French National Handball League (age: 25.06 ± 4.19 years old, height: 190.5 ± 5.73 cm; body mass: 94.2 ± 12.25 kg; years of practice: 15.94 ± 5.15 years; mean \pm SD) were recruited. All participants had equal training volume (13 h of training including one 60-min handball game per week). Exclusion criteria included any neuromuscular impairments and/or ankle, knee, hip trauma in the past 2 years and medication that might influence balance. Participants were also asked to avoid strenuous activity and the ingestion of alcohol or/and exciting substances 24 h before the experimental session. All participants voluntarily signed an informed consent form before starting the experiment, which was in accordance with the Helsinki Declaration. All procedures were approved by and performed in accordance with the relevant guidelines and regulations of the University of Pau and Adour Countries Ethics Committee. **Balance control assessment.** Participants were asked to stand barefoot and to sway as little as possible in a monopodal stance on their non-dominant leg for 25 s on a force platform (STABILOTEST TECHNO CONCEPT, Mane, France) which sampled the center of foot pressure (COP) displacements at 40 Hz. The non-dominant leg (i.e. the supporting leg, which was determined as the leg which is not used to kick a ball) was chosen because handball is an asymmetric activity which requires frequent phases of monopodal stance on the non-dominant leg (e.g. while passing, jumping and shooting). A wobble board with a diameter of 40 cm and a height of 8 cm (Balance-board, SISSEL GmbH, Bad Dürkheim, Germany) could be placed on the force platform to generate instability. For accurate and similar feet positioning between all subjects, the foot was placed according to precise landmarks on the force platform and the wobble board. Subjects had the supporting leg extended and the other leg fixed with the big toe positioned at the level of the malleolus of the other leg (without any contact). They were also asked to cross the arms in front of the chest while touching the border of the clavicle with the forefinger. Two postural tasks were considered: a stable task (STA) where participants stood on stable ground with the eyes closed (while keeping their gaze in a straight-ahead direction) and an unstable task (UNSTA) where they stood on the wobble board with the eyes open (while looking at a fixed level target at a distance of 2 m). All postural tasks were performed with or without wearing compression garments (i.e., in the CG condition and the REF condition respectively). Two familiarization trials were performed for each postural task before data

acquisition in order to avoid any learning effect (Cug et al., 2014). COP surface area (S: 90% confidence ellipse), mean COP velocity along the medio-lateral (VX) and antero-posterior (VY) axes were calculated to characterize balance control; the lower these parameters, the more efficient the balance control (Paillard and Noé, 2015). In the CG condition, progressive calf compression sleeves composed of 69% Polyamide, 21% Elastane and 10% Yarn (BOOSTER Elite, BV SPORT, Saint Etienne, France) were worn by the participants. These CG provide a pressure that increases gradually from 13 mmHg at the ankle to 19 mmHg at the gastrocnemius. CG size was individualized according to guidelines of the manufacturers, based on participants' height and calf circumference. Four sizes were used: M+, L+, XL+ and XXL+, sized for 34–38 />175, 38–43 />175, 38–43 />192, 43–48/192 (calf circumference/ height, in cm) respectively so as to accommodate all participants' body shape.

2.4. Statistical analysis

The two postural tasks (STA and UNSTA) were analyzed independently. The first step of the analysis consisted of evaluating the influence of CG with a standard whole group analysis. Since the data did not meet the assumption of normal distribution (tested with the Shapiro–Wilk test), non-parametric Wilcoxon signed rank tests were applied to compare each dependent variables (S, VX, VY) between the REF and CG conditions. A standardized principal component analysis (PCA) was also applied as a multivariate approach in order to conduct a more subtle descriptive analysis of variability between subjects, while identifying potential linear links between variables. COP parameters in the REF condition and the relative differences (RD) of each COP parameter between both conditions ($RD=100*[CG-REF]/REF$) were used as input values in the PCA. RD is an easily interpretable descriptor, which limits the influence of the heterogeneity between participants in the REF condition and makes it easy to differentiate participants who benefit from CG wearing (negative value of RD) and those who do not (positive value of RD). Finally, a hierarchical cluster analysis (HCA) (Ward, 1963) was used in a stepwise fashion on the basis of the principal component scores obtained from the PCA, to categorize the participants' behaviors into subgroups with similar characteristics (i.e. with low or high COP values in the REF condition and low or high RD values) (Watelain et al., 2000; White and McNair, 2002). Statistical analyses were performed with R statistical software. The significance level was set at $P<0.1$.

2.5. Results

Table 1 presents the mean values of COP parameters in the whole sample with the characteristics of each cluster. When inferential statistics were performed on the whole group,

no significant differences were observed between REF and CG conditions in the STA postural task. Nevertheless, strong tendencies could be observed on VX and VY, which tended to be reduced in CG compared to the REF condition ($V=92$; $P=0.073$ and $V=91$; $P=0.083$). In the UNSTA postural task, no statistically significant differences or tendencies were observed between both conditions. In the STA postural task, PCA resulted in two components that explained 70% of the total variance of the original dataset. PC1 accounted for 46.6% of the total variance and was loaded with three variables, RD_VY, RD_S and VY, which were positively correlated. PC2 explained 23.4% of the total variance and was loaded with three variables, S and VX, which were positively correlated, and RD_VX which was acting in the opposite direction (**Fig. 1a**). In the UNSTA postural task, PCA resulted in two components that explained 77.3% of the total variance of the original dataset. PC1 accounted for 54.0% of the total variance and was loaded with the three variables, VX, VY and RD_S, which were positively correlated. PC2 explained 23.3% of the total variance and was loaded with three variables, S and VY, which were positively correlated, and RD_VX which was acting in the opposite direction (**Fig. 2a**). In both postural tasks, the clustering analysis identified two clusters. The individuals' factor map (**Figs. 1b and 2b**) shows that there was a great variability between subjects and that individuals from these two clusters were mainly differentiated on the PC1 axis. Individuals from cluster 1 were located on the left side, with low values of postural parameters in the REF condition and negative values of relative difference between both conditions (**Table 1**). On the contrary, individuals from cluster 2 were located on the right side and had high values of postural parameters in the REF condition and positive values of relative difference between both conditions.

			n	REF	CS	RD
STA	S	Whole group	15	1978,2 (536.3)	1822,4 (736.7)	-7,9 (25.1)
		Cluster 1	8	1725,8 (443.3)	1281,3 (301.2)	-22,1 (22.6)*
		Cluster 2	7	2266,8 (509.8)	2440,8 (569.1)	8,5 (17.0)*
	VX	Whole group	15	59.4 (15.2)	54.8 (15.0)	-7.2 (16.0)
		Cluster 1	8	52.3 (4.4)	44.9 (8.5)	-14.2 (14.2)
		Cluster 2	7	67.5 (19.3)	66.1 (12.9)	0.7 (15.1)
	VY	Whole group	15	46.7 (13.8)	43.1 (17.5)	-9.7 (18.8)
		Cluster 1	8	38.7 (4.4)*	30.0 (5.9)	-22.6 (12.7)*
		Cluster 2	7	55.9 (15.3)*	58.0 (13.5)	5.0 (12.7)*
UNSTA	S	Whole group	15	707.0 (206.9)	648.7 (369.3)	-9.7 (38.8)
		Cluster 1	8	610.3 (130.6)	481.7 (201.2)	-21.3 (28.1)
		Cluster 2	7	817.5 (230.7)	839.6 (437.4)	3.5 (47,0)
	VX	Whole group	15	31.8 (12.2)	34.5 (17.7)	5.5 (16.9)
		Cluster 1	8	23.2 (6.6) *	22.2 (5.1)	-2.9 (13.5) *
		Cluster 2	7	41.6 (9.4) *	48.6 (16.4)	15.1 (15.9) *
	VY	Whole group	15	23.4 (7.1)	22.3 (7.7)	-5.3 (12.8)
		Cluster 1	8	18.5 (5.1) *	16.1 (3.8)	-11.9 (8.9) *
		Cluster 2	7	29.0 (4.2) *	29.4 (3.5)	2.2 (12.9) *

Table1. COP parameters of the whole group with cluster characteristics in the different postural tasks and experimental conditions. Data are expressed as mean (SD). STA stable postural task with the eyes closed, UNSTA unstable postural task with the eyes open, REF reference condition, CG compression garments condition, S COP surface area, VX and VY mean COP velocity along the medio-lateral and antero-posterior axes respectively, RD relative difference between both conditions ($RD=100*[CG-REF]/REF$). §illustrates a tendency from whole group statistics ($0.05 \leq P < 0.1$) between REF and CG conditions.

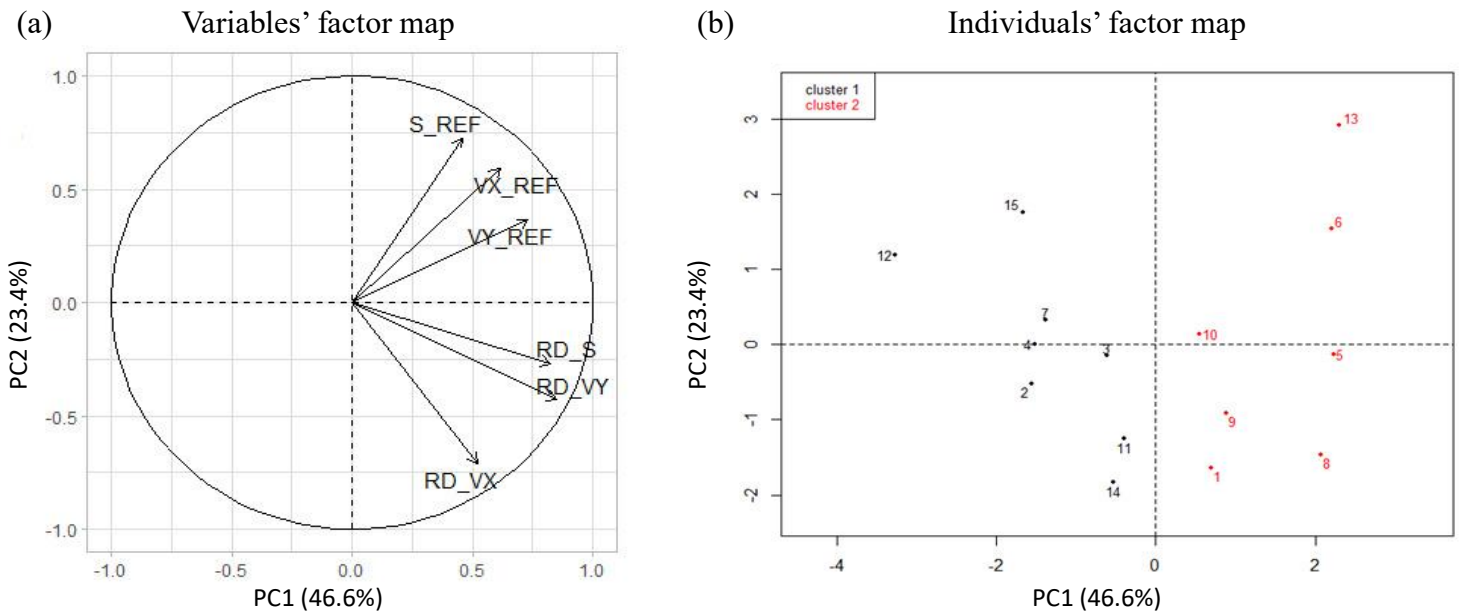


Figure 1. Variables' (a) and individuals' (b) factor map of the PCA applied on COP parameters in the STA postural task. Individuals from cluster 1 and 2 are represented by black and red dots respectively. *S_REF* COP surface area in the REF condition, *VX_REF* mean COP velocity along the medio-lateral axis in the REF condition, *VY_REF* mean COP velocity along the antero-posterior axis in the REF condition, *RD_S*, *RD_VX* and *RD_VY* relative difference between both conditions ($RD=100*[CG-REF]/REF$) of *S*, *VX* and *VY* variables

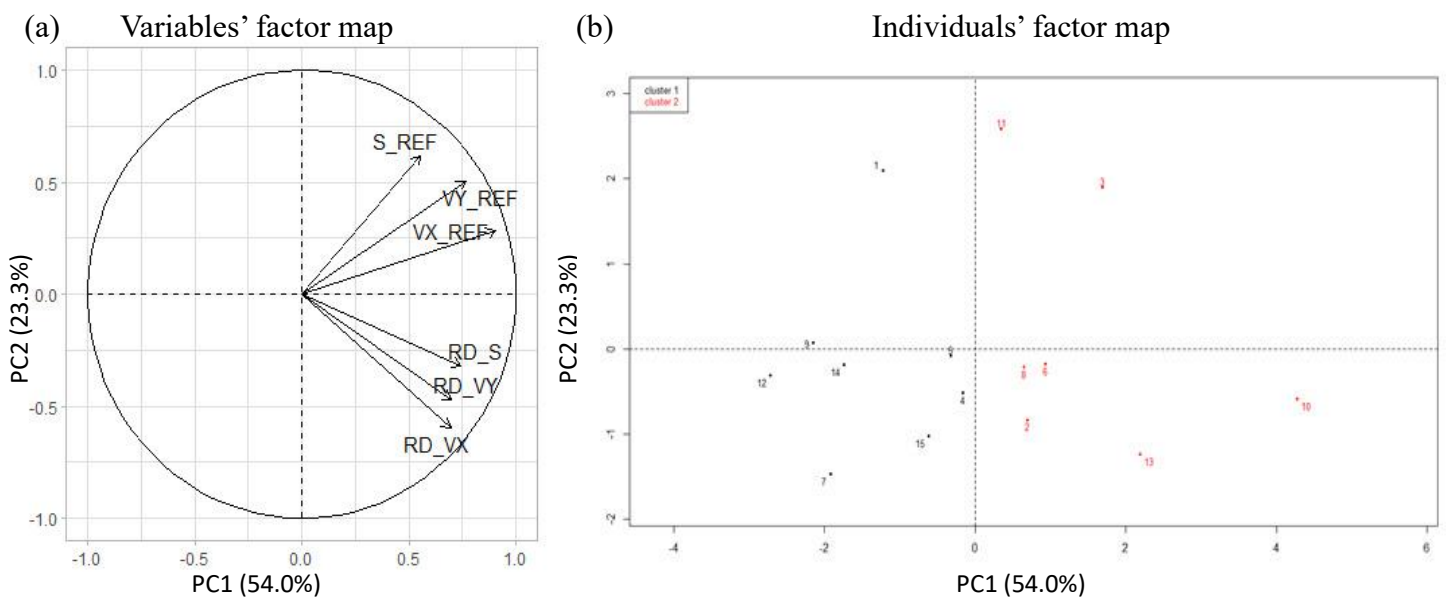


Figure 2. Variables' (a) and individuals' (b) factor map of the PCA applied on COP parameters in the UNSTA postural task. Individuals from cluster 1 and 2 are represented by black and red dots respectively. *S_REF* COP surface area in the REF condition, *VX_REF* mean COP velocity along the medio-lateral axis in the REF condition, *VY_REF* mean COP velocity along the antero-posterior axis in the REF condition, *RD_S*, *RD_VX* and *RD_VY* relative difference between both conditions ($RD=100*[CG-REF]/REF$) of *S*, *VX* and *VY* variables.

2.6. Discussion

The aim of this study was to analyze the acute effects of wearing CG on the monopodal balance control in elite professional handball players. When considering data from the whole sample, results from inferential statistics were not consistent with the hypothesis that CG would improve balance control, since the wearing of CG only induced tendencies to an improved monopodal balance control in the STA postural task. The HCA approach was successful in identifying two distinct and homogeneous subgroups of participants, thus illustrating that high inter-individual variability in the ability to benefit from CG wearing to improve balance control is present within a group of high-level athletes. CG act by applying frictional forces to the skin, which direction and size are related to the body sway movements (Michael et al., 2014). As initially observed in studies about the effects of passive tactile cues on balance control (Rogers et al., 2001), these forces activate both slow and fast-adapting cutaneous mechanoreceptors to provide additional sensory cues that are integrated by the central nervous system to reduce body sway when a sensory pathway critical for standing posture has been perturbed (e.g. when vision is occluded). The stimulation of cutaneous inputs from the lower leg induced by the wearing of CG can also depress the H-reflex by activating Ia inhibitory interneurons (Espeit et al., 2017). Because an early spinal reflex can provoke small reactive and uncontrolled movements that can be a source of postural instability (McIlroy et al., 2003), there is a relationship between the amplitude of the H-reflex and that of the displacement of the COP: the lower the amplitude of the H-reflex, the lower the postural sway (Chen and Zhou, 2011; McIlroy et al., 2003). Even though the differences in COP parameters were not statistically significant among experimental conditions, the tendencies to an improved balance control with CG ($P=0.073$ and $P=0.083$ for VX and VY respectively) could reflect an efficient sensory reweighting mechanism (Peterka, 2002) with an up-weighting of the additional cutaneous information provided by CG to compensate for the lack of visual cues in the STA postural task. Indeed, garments that stimulate lower limbs cutaneous receptors (e.g. CG, braces and tapes) rather positively influence balance control when somatosensory information is altered by experimental manipulations (Michael et al., 2014; Smalley et al., 2018; Yalla et al., 2014). These garments had more limited effects when standing on unstable supports (e.g. wobble board as in the present study) or performing dynamic tasks (e.g. Y balance test) (Cavanaugh et al., 2016; Jaakkola et al., 2017), likely due to the availability of visual cues and the increased contribution of vestibular and proprioceptive cues due to greater joint movements (Ivanenko et al., 2000) which might have limited an up-weighting of the additional somatosensory cues provided by CG. Results from the PCA showed that there was a high variability between individuals' responses to CG wearing within a population of

professional elite athletes. This heterogeneity among the ability of participants to benefit from CG wearing to improve balance control could explain the controversial results about the influence of compression garments on balance control in healthy young subjects (Cavanaugh et al., 2016; Jaakkola et al., 2017; Michael et al., 2014; Woo et al., 2018, 2017; You et al., 2004). In both STA and UNSTA postural tasks, the HCA also provided evidence that this variability did not present a random structure, but was structured in two clusters of participants with similar characteristics. Subjects from cluster 1, while presenting lower values of postural variables in the REF condition, exhibited a more efficient balance control at baseline than subjects from cluster 2. Interestingly, only subjects from cluster 1 benefited from CG wearing to improve their balance control, while presenting negative values of RD of COP parameters between CG and REF condition. Individuals from cluster 2 presented positive value of RD and did not benefit from CG wearing. This link between balance control efficiency at baseline and the ability to take advantage of CG to improve balance control can potentially stem from (1) differences in participant's preferred sensorimotor tactics and/or (2) differences in participants' intrinsic balance/proprioceptive abilities. Individuals vary in the degree to which they weight sensory inputs to control their balance (Peterka, 2002). Earlier reports about sensory reweighting in balance control during sensory perturbations have provided evidence that subjects from a homogeneous sample could respond differently to sensory perturbations depending on preferred modes of spatial referencing (Isableu and Vuillerme, 2006; Pavailler et al., 2016). Two main preferred sensorimotor tactics have been identified. Some subjects, called support-dependent, rely more on the exploitation of the geometry of the support surface as a reference frame by assigning a high weight to somatosensory cues from ankle-foot proprioceptive and plantar cutaneous mechanoreceptors. Other subjects, called gravity-dependent, rely more on gravito-inertial signals by assigning a high weight to kinetic-graviceptive vestibular cues and/or to proprioceptive cues stemming from joints and muscles with a higher position in the kinematic chain (i.e. hip, trunk and neck joint muscles) (Isableu and Vuillerme, 2006; Pavailler et al., 2016). Isableu et Vuillerme (2006) showed that subjects who had to sway as little as possible on stable ground with the eyes closed differently regulated their balance according to their preferred sensorimotor tactics). Support-dependent subjects swayed less than gravity-dependant subjects, by minimizing angular variations of the ankle with respect to the support. On the other hand, gravity-dependent subjects exhibited larger postural sway while adopting a more exploratory behaviors in order to extract kinetic-graviceptive information more efficiently (Isableu and Vuillerme, 2006). In the present study, individuals from cluster 1, who swayed less than those from cluster 2, had a typical profile of

support-dependent subjects, while individuals from cluster 2 may be characterized as gravity-dependent subjects. Isableu et Vuillerme (2006) also showed that support-dependent subjects were more sensitive to somatosensory alteration of the feet-support than gravity-dependent ones. In the same manner, individuals from cluster 1 exhibited a greater sensitivity to somatosensory manipulation by being the only participants to take advantage of CG to improve balance control, thus supporting the idea that they would present a support-dependent preferred sensorimotor tactic. Even though athletes exhibit better balance control than non-athletes (Hrysomallis, 2011; Paillard, 2017) such a heterogeneity of balance regulation mechanisms within our group of athletes might also stem from individual natural predispositions that would persist despite years of training (Paillard, 2019). It is known that the contribution of proprioception in balance regulation is increased in athletes and that elite athletes have superior proprioceptive abilities than sub-elite or non-athletes (Han et al., 2015; Paillard, 2017). Nevertheless, (Han et al., 2015) showed that superior proprioceptive abilities in high-level athletes was not correlated with training experience but was rather constrained by genetically determined factors. Hence, it can be hypothesized that athletes from cluster 1 had exceptional neurobiologically determined proprioceptive acuity that enabled them to benefit from CG wearing through optimal sensory reweighting. The ability to take advantage of garments that stimulate cutaneous receptors such as CG to improve balance control seems to describe a U-shaped relationship according to subjects' balance and/or proprioceptive abilities. Beneficial effects are reported in individuals with poor proprioceptive acuity and/or balance (Wang et al., 2019; You et al., 2004) and with individuals with good proprioceptive acuity and/or balance¹³, whereas no beneficial effects are reported in healthy non-athletes subjects with “ordinary” balance and/or proprioceptive acuity (Cavanaugh et al., 2016; Hijmans et al., 2009; Jaakkola et al., 2017; You et al., 2004). A limitation of the study is that although CG were individually fitted by choosing proper sizing according to the individual calf size and height, we did not measure the interface pressure applied by the CG. According to the manufacturer's information, the CG used in this study are expected to provide a 19 mmHg pressure level over the calf. Due to the sizing issue, however, it is possible that 19 mmHg is not always the pressure actually applied. For example, with a M size suitable for a 38–43 cm calf circumference range, the pressure exerted by the CG should be higher with a circumference of 43 cm compared to 38 cm. In this case, the more intense pressure on the skin may provide a greater cutaneous stimulus with a larger impact on balance control. The fact that a commercially manufactured CG does not provide a homogeneous compression level with the same size might modulate the effects of CG on balance control. Hence, in the present study, this could also have influenced the

distribution of the individuals within the different clusters. Nevertheless, studies that have tested the effects of wearing CG of different compression levels reported that the level of compression had no influence on balance control (Sperlich et al., 2013; Woo et al., 2018, 2014), thus suggesting that the level of compression is not the most crucial factor that modulates the effects of CG on balance control. However, future studies should be conducted to specifically examine the influence of compression heterogeneity actually provided by a CG model of a given size on balance control. Further experiments are also needed to assess athletes' preferred sensorimotor tactics (through sensory perturbation paradigms) and intrinsic proprioceptive abilities in order to explore the influence of these two factors on the ability of athletes to take advantage of CG to improve balance control.

Conclusions

This study showed that among a sample of professional handball players with more than 15 years' experience, only athletes with the best balance abilities at baseline could benefit from CG wearing to improve their balance control. Hence, it can be suggested that the ability to benefit from CG wearing to improve balance control depends on elite athletes' intrinsic balance abilities and/or preferred sensorimotor tactics. The present finding emphasizes the necessity to address the issue of inter-individual variability when studying the effects of CG on balance control.

3. Article 3

Can compression garments reduce inter-limb balance asymmetries ?

Frédéric Noé, Kévin Baige and Thierry Paillard

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3.1. Abstract

Sensory cues provided by compression garments (CG) can improve movement accuracy and potentially reduce inter-limb balance asymmetries and the associated risk of injury. The aim of this study was to analyze the effects of CG wearing on inter-limb balance asymmetries. The hypothesis was that CG would reduce inter-limb balance asymmetries, especially in subjects with high level of asymmetries. Twenty-five sportsmen were recruited. They had to stand as motionless as possible in a one-leg stance in two postural tasks (stable and unstable), while wearing CG or not. Asymmetry indexes were calculated from center of foot pressure parameters. The effects of CG wearing were analyzed according to participants' baseline level of asymmetry (i.e., without wearing CG) with correlation analyses. A qualitative analysis was also performed after a dichotomization procedure to check for a specific influence of CG on the dominant and non-dominant leg. Inter-limb balance asymmetries were reduced with CG in participants with high levels of asymmetries at baseline. However, asymmetries were increased with CG in participants with low levels of asymmetries at baseline. The dominant leg was more affected by this negative effect. CG wearing could reduce inter-limb balance asymmetries and the related injury risk in subjects with high levels of inter-limb balance asymmetries at baseline. Nevertheless, CG should not be used in individuals with low baseline balance asymmetries since it can increase asymmetries in these subjects, likely by confusing and overloading the sensorimotor processing on the dominant leg.

Keywords: laterality, symmetry, posture, balance control, compression garments

3.2. Introduction

Asymmetries between two limbs are prevalent in human movement. They are characterized by a difference in performance between the right and left limbs and/or the preferential use of one side of the body (i.e., left or right) to perform a motor action (Bishop et al., 2018; Schneiders et al., 2010). The etiologies of inter-limb asymmetries are related to lateralization in sensorimotor control originating from cerebral hemispheric asymmetry (Liu et al., 2021; Marcori et al., 2020; Promsri et al., 2019, 2018) and biomechanical factors (e.g., bilateral asymmetry in the bones length, imbalance of muscle strength between the left and right limb) (Auerbach and Ruff, 2006; Bishop et al., 2018). Inter-limb asymmetries can be modulated by numerous factors. Injuries and pathologies such as anterior cruciate ligament injuries (Mohammadi et al., 2012) or scoliosis (Yang et al., 2013) increase inter-limb asymmetries. Subjects affected by neurologic conditions (e.g., stroke and multiple sclerosis) and individuals with experience in asymmetric sports (e.g., soccer, volley-ball, and hand-ball) also demonstrate pronounced inter-limb asymmetries (Chisholm et al., 2011; Paillard & Noé, 2020; Pau et al., 2021). Inter-limb asymmetries can have a negative impact on sports performance and are associated with a high incidence of lower-limb injury, especially if asymmetries concern balance control (Bishop et al., 2018; Promsri et al., 2019; Stiffler et al., 2017). Actually, inter-limb balance asymmetries may impair the ability to shift the body weight onto one leg thus negatively impacting sports-related actions such as sidestepping or changes of direction and predisposing sportspeople to non-contact lower-limb injury (Bishop et al., 2018; Dos'Santos et al., 2019; Promsri et al., 2019). Therefore, training strategies such as balance training, resistance training or warm-up programs, can be implemented to minimize inter-limb balance asymmetries, improve balance control and reduce the relative risk of sports-related non-contact injury (Bishop et al., 2018; Madruga-Parera et al., 2020; Pardos-Mainer et al., 2019). Affordable external devices that interact with cutaneous receptors such as compression garments (CG) can also acutely improve balance control (Baige et al., 2020; Kuster et al., 1999; Michael et al., 2014; Woo et al., 2017). The constriction provided by CG acts as a mechanically supportive framework that can activate interacting cutaneous mechanoreceptors that individually would not have been activated (Baige et al., 2020), thus improving movement accuracy during tasks that include a large somatosensory component (Broatch et al., 2021; Ghai et al., 2018; Hasan et al., 2016) and offering a potential benefit in reducing inter-limb balance asymmetries. Nevertheless, to our knowledge, no study has specifically investigated the effects of CG wearing on inter-limb balance asymmetries. Hence, this study was undertaken to investigate the effects of CG on inter-limb balance asymmetries in individuals with extensive experience in an asymmetric sport

such as handball players. Handball is a sport involving asymmetric motor actions (lower and upper limbs) that can accentuate inter-limb asymmetries, which might negatively affect athletic performance and increase the risk of lower extremity injuries (Barrera-Domínguez et al., 2021; Paillard, 2017; Steib et al., 2016). Thus, a passive intervention such as CG wearing is hypothesized to reduce inter-limb balance asymmetries, especially in subjects with a high level of asymmetry, and could represent a cost-effective sport-related injury prevention strategy.

3.3. Materials and Methods

Participants

Twenty-five young handball players (age: 27.1 ± 6.9 years old, height: 184.8 ± 8.1 cm; body mass: 87.2 ± 15.3 kg; mean \pm SD) who reported no neuromuscular problems in the past 2 years volunteered for the current study. Participants were recruited from two regional semi-professional teams. They were asked to avoid strenuous activity and the ingestion of alcohol or/and excitatory substances 24 h before the experimental session. A written informed consent was obtained from all participants before starting the experiment, which was in accordance with the Declaration of Helsinki. All procedures were approved by and performed in accordance with the relevant guidelines and regulations of the University of Pau and Pays de l'Adour Ethics Committee.

Apparatus and Procedure

Participants were asked to sway and move as little as possible when standing barefoot in a one-leg stance for 25 s on a force platform (Stabilotest R Techno ConceptTM, Mane, France) which sampled the displacements of the center of foot pressure (position of the point of application of the vertical ground reaction force) at 40 Hz. Two postural tasks were conducted: a stable task where participants stood directly on the force platform (on stable ground) with their eyes closed (while keeping their gaze straight ahead) and an unstable task where they stood with their eyes open (while looking at a fixed level target at a distance of 2 m) on a wobble board with a diameter of 40 cm and a height of 8 cm (Balance-board, Sissel R GmbH, Bad Dürkheim, Germany) which was placed on the force platform to generate instability. For accurate and similar feet positioning between all participants, the platform and the wobble board were marked with a central horizontal line, and participants were required to align the middle of the foot with the mark (the middle of each foot was delimited beforehand). The center of the wobble board was also aligned with the center of the force platform. Postural tasks were performed with or without wearing compression garments (CG and REF condition, respectively). In the

CG condition, calf compression sleeves (Booster, BV sport R , Saint Etienne, France) made of 79% Polyamide and 21% Elastane, were worn by the participants (**Figure 1**). According to the manufacturer's specifications, these garments provide a pressure that increases gradually from 13 mmHg at the lower part of the calf to 20–25 mmHg at the gastrocnemius belly (20 mmHg at the lateral part and 25 mmHg at the medial part). The size of the compression sleeves was individually fitted according to guidelines of the manufacturers, based on participants' height and calf circumference. Four sizes were used: M+, L+, XL+, and XXL+, sized for 34–38/>175, 38–43/>175, 38–43/>192, 43–48/192 (calf circumference/height, in cm), respectively, so as to accommodate all participants' body shape. Participants performed a set of three trials in each postural task (stable and unstable) and condition (REF and CG) with each set completed in a randomized order to avoid any learning effect. The first two trials were not recorded and served as familiarization trials. Since a stable and reliable balance score is achieved at the third trial in a one one-leg stance (Cug et al., 2014), only the third trial was recorded and considered for statistical analysis for each postural task and in each experimental condition. Subjects were sitting quietly on a chair for 2 min between balance assessments.



Figure 1. Compression sleeves worn by participants in the compression

Analysis of Data

The following parameters of the center of pressure were initially calculated: mean velocity (sum of the cumulated COP displacement divided by the trial time) along the medio-lateral (VX) and antero-posterior (VY) axes and surface area (S: 90%confidence ellipse) (Paillard & Noé, 2015). Based on the method proposed by (Read et al., 2018) and (Fort-Vanmeerhaeghe

et al., 2020), an asymmetry index (ASY) between both legs was then calculated for each center of pressure parameter (ASY_VX, ASY_VY, ASY_S) as follows:

$$ASY(\%) = ABS \left(\frac{\text{Highest performing limb} - \text{Lowest performing limb}}{\text{Highest performing limb}} \right) \times 100,$$

with ABS: absolute value.

When considering that with participants who were asked to sway as little as possible when standing upright, the lower the center of pressure parameters (i.e., VX, VY, S), the more efficient the balance control (Paillard & Noé, 2015), the highest performing limb was then defined as the side with the lowest center of pressure value.

3.4. Statistical analysis

The two postural tasks (stable and unstable) were analyzed independently. Normality was tested using the Shapiro–Wilk test. As the dependent variables (ASY_VX, ASY_VY, and ASY_S) did not meet the assumption of normal distribution, non-parametric Wilcoxon sign rank tests were applied to determine differences between the CG and REF conditions. The difference of each asymmetry index between the CG and REF conditions (difference = CG - REF) was also calculated to easily differentiate participants who benefit from CG wearing to reduce inter-limb balance asymmetries (negative difference) and those who do not (positive difference). Then, Spearman's rank order correlations were undertaken between asymmetry indexes at baseline (i.e., in the REF condition) and differences in asymmetry between the REF and CG conditions to assess whether the beneficial effects of CG in reducing inter-limb balance asymmetries was related to the participant's inter-limb balance asymmetries at baseline. A qualitative analysis was also carried out to check for a specific influence of compression garments on balance control of the dominant and non-dominant leg, determined by the preferred kicking leg (Paillard & Noé, 2020). A dichotomization method was performed on the center of pressure parameters to characterize three levels of CG influence on balance control: a negative influence, a negligible influence and a positive influence. The following are the thresholds used in the dichotomization procedure: a negative influence was considered when the value in the CG condition exceeded that in the REF condition by more than 10%; a negligible influence was considered when the difference between either conditions did not exceed 10%; a positive influence was considered when the value in the REF condition exceeded that in the CG condition by more than 10%. χ^2 -conformity tests were independently performed on DL and NDL data to test the null hypothesis (similar distribution of individuals for whom CG have a negative, negligible, or positive influence on balance control). This qualitative analysis was

performed on the whole sample and on subgroups of individuals in order to check whether individuals who benefited from CG to decrease inter-limb balance asymmetries and those who do not were differently affected by the wearing of CG on the dominant and non-dominant leg. Sub-groups were formed by distinguishing subjects in whom CG wearing had no substantial influence on asymmetry indexes (“unchanged asymmetry with CG” subgroup, i.e., with an increase/decrease of the asymmetry index between REF and CG conditions of less than 10%), subjects in whom CG wearing markedly increased the level of asymmetry (“increase in asymmetry with CG” subgroup, i.e., with an increase of the asymmetry index of more than 10% in the CG condition) and subjects in whom CG wearing markedly decreased the level of asymmetry (“decrease in asymmetry with CG” subgroup, i.e., with a decrease of the asymmetry index of more than 10% in the CG condition). Based on previous studies about reliability of center of pressure-based postural sway measures during one-leg stance in young healthy participants, the 10% threshold was chosen to distinguish between clear and unclear changes due to measurement noise (Da Silva et al., 2013; Lin et al., 2013; Muehlbauer et al., 2011). The relationships between subgroups of individuals and specific influence of CG on the dominant and non-dominant leg were then tested with the Fisher’s exact test after having constructed contingency tables. Statistical analyses were performed with R statistical software. The significance level was set at $p < 0.05$.

3.5. Results

Figure 2 illustrates boxplots with individual data points of asymmetry indexes in the REF and CG conditions. No significant differences were observed between REF and CG conditions in both the stable and unstable postural tasks. When focusing on the individual data points, one could notice that the asymmetry indexes did not evolve similarly among participants between the REF and CG conditions: asymmetry indexes increased with CG in some participants (red dotted lines on **Figure 2**), while asymmetry indexes decreased with CG in others (blue dotted lines on **Figure 2**). Scatterplots illustrating correlations between ASY indexes in the REF condition and the differences between the CG and REF conditions are shown in **Figure 3**. In both stable and unstable postural tasks and for all asymmetry indexes, there were significant and large relationships between asymmetry indexes in the REF condition and asymmetry differences between CG and REF conditions. This result indicates that high levels of inter-limb balance asymmetry at baseline [approximate (40–120%) range of asymmetry] was associated with negative differences between CG and REF conditions (i.e., a beneficial effect of CG wearing in reducing inter-limb balance asymmetries). On the contrary, low levels of inter-limb

balance asymmetry at baseline [approximate (0–40%) range of asymmetry] were rather associated with positive differences between CG and REF conditions (i.e., an increase of inter-limb balance asymmetries when wearing CG). **Table 1** shows the distribution of participants according to the influence of CG wearing (negative, negligible, or positive influence) on balance control of the dominant and non-dominant leg in the whole sample and in subgroups of individuals. In the stable postural task, results from χ^2 conformity tests performed in the whole sample were not significant, thus illustrating a homogeneous distribution among participants with a negative, negligible or positive influence of CG wearing on balance control of the dominant or the non-dominant leg. In this postural task, results from the Fisher's exact test were also not significant. In the unstable postural task, results from the χ^2 conformity test applied on participants' distribution based on S data on the dominant-leg showed a significant difference from an equal distribution ($\chi^2 = 6.08$; $p < 0.05$), with an under-representation of individuals for whom CG wearing had negligible influence on the dominant-leg. When the χ^2 test was applied on participants' distribution based on VY data on the non-dominant leg, a significant difference from an equal distribution ($\chi^2 = 11.12$; $p < 0.004$), with an over-representation of individuals for whom CG wearing had negligible influence on balance control of the non-dominant leg. Results from the Fisher's exact test showed a significant association between subgroups of participants and CG influence on balance control on the dominant leg when participants' distribution were based on VX ($p < 0.003$) and VY data ($p < 0.005$). Individuals in whom CG wearing markedly increased the level of asymmetry were negatively influenced by CG wearing on the dominant leg. Results from the Fisher's exact test did not show any significant association between subgroups of participants and CG influence on balance control of the non-dominant leg.

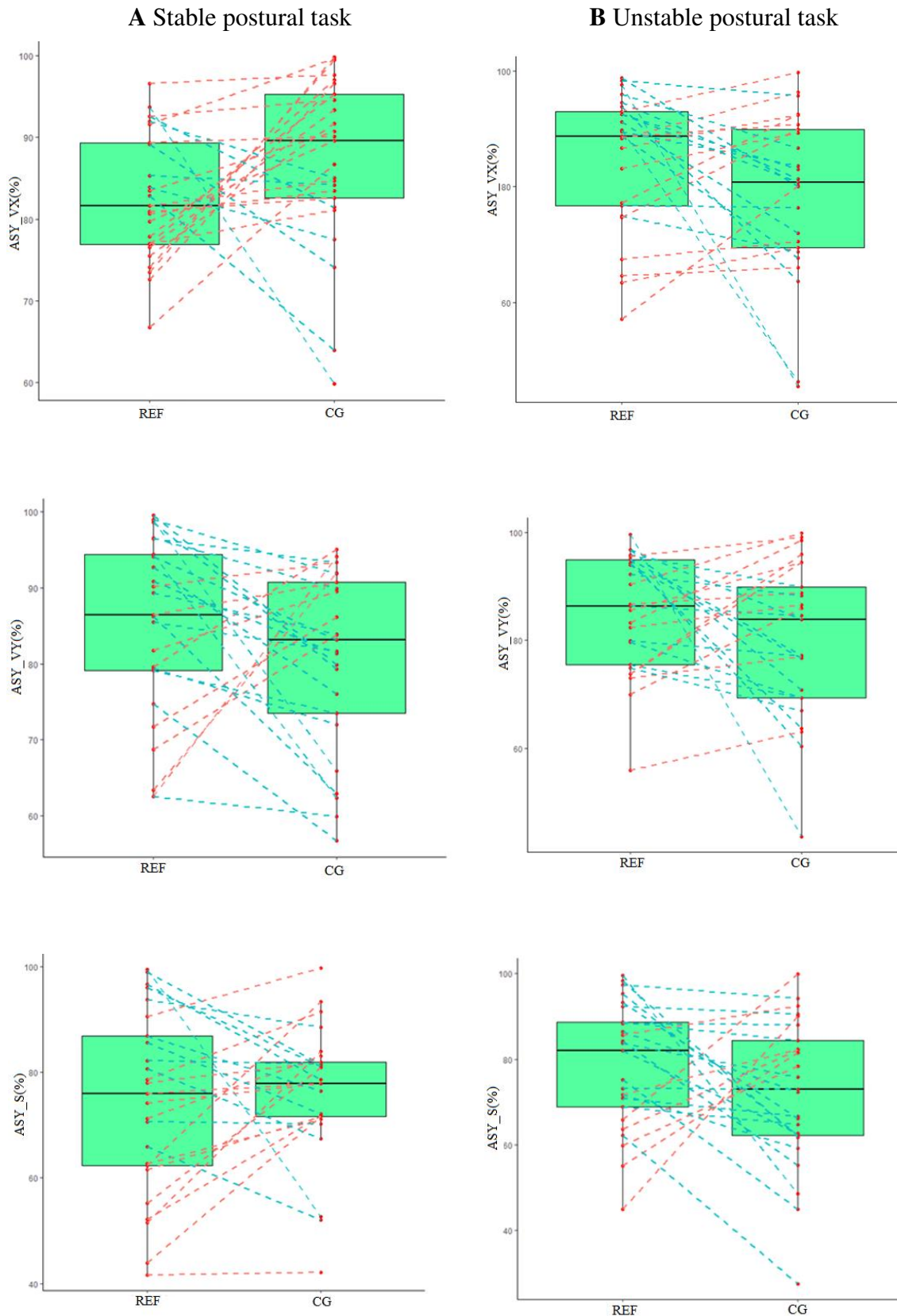


Figure 2. Boxplot representation with individual data points of center of pressure asymmetry indexes in the reference (REF) and compression garments (CG) conditions in (A) the stable postural task and (B) the unstable postural task. The red dotted lines illustrate individuals whose asymmetry indexes increase with CG while the blue dotted lines show individuals whose asymmetry indexes decrease with CG

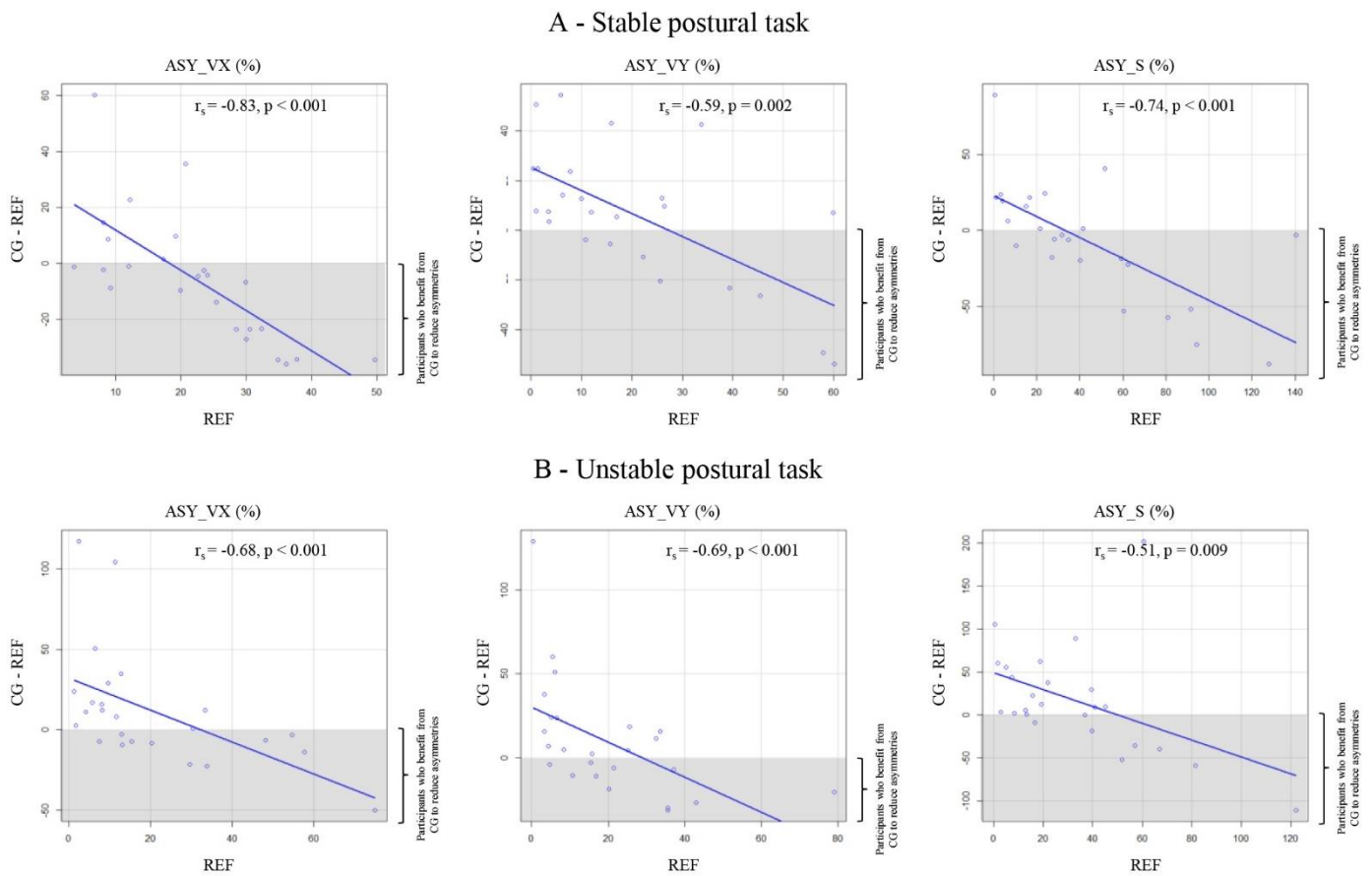


Figure 3. Scatterplots representing the correlations between asymmetry indexes (ASY_VX, ASY_VY, and ASY_S) in the REF condition and the differences in asymmetry between REF and compression garments (CG) conditions (CG-REF) in (A) the stable postural task and (B) the unstable postural task. Gray areas correspond to participants who benefit from CG wearing to reduce inter-limb balance asymmetries (negative difference). Blank areas correspond to participants who do not benefit from CG wearing to reduce inter-limb balance asymmetries (positive difference). r_s : Spearman's rank correlation coefficient.

			Stable task			Unstable task			
			Negative	Negligible	Positive	Negative	Negligible	Positive	
VX	Whole sample	Dominant leg	9	10	6	10	9	6	
		Non-dominant leg	5	12	8	8	11	6	
	Subgroups	Decrease in asymmetry with CG	Dominant leg	5	2	3	4	0	3
			Non-dominant leg	2	4	4	1	3	3
		Unchanged asymmetry with CG	Dominant leg	1	6	2	0	6	0
			Non-dominant leg	1	6	2	1	5	0
	Increase in asymmetry with CG	Dominant leg	3	2	1	6	3	3	
		Non-dominant leg	2	2	2	6	3	3	
VY	Whole sample	Dominant leg	10	8	7	10	7	8	
		Non-dominant leg	6	10	9	3	16	6	
	Subgroups	Decrease in asymmetry with CG	Dominant leg	3	2	3	3	3	3
			Non-dominant leg	1	4	3	2	5	2
		Unchanged asymmetry with CG	Dominant leg	1	1	0	0	4	0
			Non-dominant leg	1	1	0	0	4	0
	Increase in asymmetry with CG	Dominant leg	6	5	4	7	0	5	
		Non-dominant leg	4	5	6	1	7	4	
S	Whole sample	Dominant leg	11	3	11	13	3	9	
		Non-dominant leg	9	7	9	8	8	9	
	Subgroups	Decrease in asymmetry with CG	Dominant leg	3	2	7	4	0	3
			Non-dominant leg	6	3	3	2	3	2
		Unchanged asymmetry with CG	Dominant leg	1	1	2	1	2	1
			Non-dominant leg	0	1	3	0	3	1
	Increase in asymmetry with CG	Dominant leg	7	0	2	8	1	5	
		Non-dominant leg	3	3	3	6	2	6	

Table 1. Distribution of participants according to the influence of compression garments (CG) wearing (negative, negligible, or positive) on the dominant and non-dominant leg in the whole sample and in subgroups of individuals.

Subgroups of individuals were formed by distinguishing subjects in whom CG wearing had no substantial influence on asymmetry indexes (“unchanged asymmetry with CG” subgroup), subjects in whom CG wearing markedly increased the level of asymmetry (“increase in asymmetry with CG” subgroup) and subjects in whom CG wearing markedly decreased the level of asymmetry (“decrease in asymmetry with CG” subgroup). VX, mean velocity of the center of pressure along the medio-lateral axis; VY, mean velocity of the center of pressure along the antero-posterior axis; S, center of pressure surface area (90% confidence ellipse).

3.6. Discussion

The aim of this study was to analyze the effects of CG wearing on inter-limb balance asymmetries. The hypothesis was that CG would reduce inter-limb balance asymmetries, especially in subjects with high level of asymmetries. When using a standard statistical approach with pairwise comparisons between group levels, our results showed that the wearing of CG was not associated with a significant reduction of inter-limb balance asymmetries. However, when analyzing the effect of CG wearing according to participants' initial level of asymmetry, results from correlation analyses indicated that beneficial effects of CG in reducing inter-limb balance asymmetries were related to participant's asymmetry levels at baseline. Only participants with high levels of inter-limb balance asymmetries at baseline benefited from CG to decrease inter-limb balance asymmetries. Inter-limb balance asymmetries are mainly related to differences in somatosensory processing between both legs originating from cerebral hemispheric asymmetry (Liu et al., 2021; Marcori et al., 2020; Promsri et al., 2019, 2018). Within the perspective of the dynamic dominance model of laterality (Sainburg, 2014, 2005), one hemisphere (the left hemisphere for right-handed individuals) would rather be specialized in limb trajectory control, whereas the other hemisphere would rather be specialized for impedance control-i.e., control of limb position and maintenance of a stable posture (Marcori et al., 2020; Sainburg, 2014, 2005). Lateralization of impedance control is based on hemisphere specialization for the utilization of somatosensory cues (Goble et al., 2006; Liu et al., 2021; Sainburg, 2014), which is characterized by the superiority of one hemisphere in processing somatosensory information (the right hemisphere for right-handed individuals), thus resulting in better proprioception of one limb (the left limb for right-handed individuals) compared to the other (Carnahan & Elliott, 1987; Goble et al., 2006). Participants' injury history and/or experience in asymmetric motor practices can modulate lateralization of impedance control and increase the difference in somatosensory processing between the two legs, thus inducing large inter-individual differences of balance inter-limb asymmetry (Marcori et al., 2019; Paillard & Noé, 2020). When wearing CG, frictional forces that activate both slow and fast-adapting cutaneous mechanoreceptors are applied to the skin, which can improve joint position sense and balance control (Baige et al., 2020; Broatch et al., 2021; Cameron et al., 2008; Kuster et al., 1999; Michael et al., 2014; Woo et al., 2017; You et al., 2004). In the present study, there was a great heterogeneity in the ability of participants to benefit from CG wearing to reduce inter-limb balance asymmetries. Previous studies about the effects of CG on functional somatosensory abilities have produced concordant findings while reporting a strong inter-individual variability in responses to the wearing of CG in young healthy participants (Broatch

et al., 2021; Cameron et al., 2008; You et al., 2004). After ranking participants according to their score in a movement discrimination task, these studies showed that only participants with poor lower limb somatosensation benefited from the wearing of CG to improve joint position sense, thus illustrating that the magnitude of the beneficial effects of CG wearing was inversely related to the participant's somatosensation at baseline. Similar findings were observed with other stimulation strategies such as ankle taping (Long et al., 2017), textured insoles (Steinberg et al., 2016), and vibration stimulation (Liu et al., 2021). In the present study, participants with high levels of inter-limb balance asymmetries at baseline benefited from CG wearing to reduce inter-limb balance asymmetries. However, in both the stable and unstable postural tasks, the data from the qualitative analysis about the specific influence of CG on both legs (**Table 1**) did not illustrate a stronger influence of CG on the dominant leg or the non-dominant leg in individuals who benefited from CG wearing to markedly decrease inter-limb asymmetries. In participants with low levels of inter-limb balance asymmetries at baseline, CG were unhelpful and could also increase inter-limb-balance asymmetries in some participants. Further studies reported analogous findings while showing that proprioceptive acuity decreased in participants with higher levels of proprioceptive ability when they wore external devices that stimulate cutaneous receptors (Cameron et al., 2008; Liu et al., 2021; Long et al., 2017; Steinberg et al., 2016). These authors postulated that in subjects with a high proprioceptive acuity at baseline, the application of an external stimulation device confused and overloaded the sensorimotor system by delivering redundant information, thus resulting in an impaired proprioceptive ability. Liu et al. (2021) noticed that proprioception deteriorated only in the dominant leg in individuals with high proprioceptive acuity following stimulation of the calf muscles with a vibrating foam roller. Our results from the qualitative analysis also suggest that, in the most challenging postural task (i.e., the unstable postural task) CG wearing would have a greater impact on the dominant leg and, more specifically, that CG negatively influenced balance control only on the dominant leg in participants in whom CG wearing increased inter-limb asymmetries. Our results therefore seem to confirm the hypothesis formulated by Liu et al. (2021) about different effects of the application of external stimuli on different hemispheres and show that the non-dominant hemisphere would be less sensitive to somatosensory stimulation. A limitation of the current research is the absence of measure of the pressure exerted by the calf compression sleeves. Although compression sleeves were individually fitted by following the manufacturer's specifications and choosing proper sizing according to individuals' calf circumference, commercially manufactured compression garments do not provide exactly the same level of compression in all subjects. Potential differences in the

pressures exerted by the CG might modulate the effects of CG on inter-limb balance asymmetries. Nevertheless, studies that have tested the effects of CG providing various compression levels on balance control did not report any significant differences attributed to the level of compression (e.g., (Hijmans et al., 2009; Jaakkola et al., 2017; Woo et al., 2018). It should be noted that the compression sleeves used in this study did not cover the ankle joint, whereas somatosensory information from the ankle joint plays an essential role in balance control (Han et al., 2015). Hence, one can hypothesize that the use of CG covering the ankle joints such as compression socks could potentially provide larger benefits in reducing inter-limb balance asymmetries. Further experiments are needed to explore the influence of various designs of CG (e.g., full leg CG, compression socks, calf and knee compression sleeves) on inter-limb balance asymmetries. The present study provides new insights about the influence of CG on inter-limb balance asymmetries. From a practical point of view, these results suggest that CG wearing could reduce inter-limb balance asymmetries and the related injury risk in participants with high levels of inter-limb balance asymmetries at baseline. In return, since it rather increases asymmetries in participants having low baseline balance asymmetries, CG wearing should be avoided in these participants.

Partie III - Discussion et conclusion générale

1. Rappel des résultats

L'objectif général de ce travail de thèse était d'analyser les effets aigus du port de vêtements de compression sur le contrôle postural chez différents publics, en appréhendant la problématique de la variabilité interindividuelle. Une première étude a été réalisée afin d'évaluer ces effets chez des sujets actifs en bonne santé. Dans une seconde étude, nous nous sommes intéressés aux effets des vêtements de compression sur le contrôle postural d'athlètes de haut niveau. Une troisième étude a enfin été réalisée pour spécifier l'influence des vêtements de compression sur les asymétries d'équilibre postural inter-membres. Dans toutes ces études, les effets des vêtements de compression ont été évalués d'une part à l'échelle globale de l'échantillon testé, et d'autre part en fonction des différentes réponses observées au sein d'un même échantillon à l'aide de méthodes statistiques dédiées (e.g. analyses en cluster).

Quel que soit le public testé (sujets actifs en bonne santé ou athlètes de haut niveau), les analyses réalisées à l'échelle globale de l'échantillon n'ont pas permis de mettre en évidence un bénéfice significatif des vêtements de compression sur le contrôle postural. Cependant, en se focalisant plus spécifiquement sur les différences interindividuelles des réponses associées au port des vêtements de compression, les résultats ont permis de mettre en évidence des améliorations du contrôle postural chez certains sujets présentant des caractéristiques spécifiques.

2. Discussion

La littérature scientifique laisse apparaître des résultats contradictoires parmi les études qui traitent de la stimulation tactile par le port de vêtements de compression (compression garments : CG). En effet, alors que certaines études rapportent un effet significatif des CG sur le contrôle postural (Kuster et al., 1999; Michael et al., 2014; Palm et al., 2012; Woo et al., 2018; You et al., 2004) d'autres ne révèlent aucun bénéfice particulier attribuable aux CG (Cavanaugh et al., 2016; Hijmans et al., 2009; Jaakkola et al., 2017; Sperlich et al., 2013; Woo et al., 2014). Il n'y a donc pas vraiment de consensus quant aux bénéfices potentiels des CG sur le contrôle de l'équilibre. Les différences entre la pluralité des conditions expérimentales peuvent expliquer l'hétérogénéité des résultats. Effectivement, les manipulations expérimentales (position statique ou dynamique, privation visuelle, support instable, posture bipodale ou monopodale) influencent la pondération des entrées sensorielles (Peterka, 2018). Par exemple, dans une situation de privation des entrées visuelles, un mécanisme de repondération s'opère en faveur des entrées somatosensorielles qui bénéficient au port de manchons de compression (Michael et al., 2014). Au contraire, des conditions expérimentales peu contraignantes (yeux ouverts) peuvent expliquer l'absence d'effet significatif (Cavanaugh

et al., 2016). Il semblerait aussi que les personnes âgées (Lopes et al., 2014; Woo et al., 2021, 2018) répondent plus favorablement à la compression que les adultes plus jeunes (Hijmans et al., 2009). Des modifications de la morphologie des récepteurs cutanés au cours du vieillissement ont été observées et associées à une réduction de l'activité neuronale, qui augmente le seuil sensoriel et vibratoire nécessaire à une perception précise du stimuli tactile (Woo et al., 2017) prédisposant les personnes âgées à des risques de chute (Deschamps et al., 2016). Ainsi par un phénomène de résonance stochastique, l'ajout de bruit du dispositif compressif permet d'améliorer le contrôle postural monopodal des sujets âgés. L'application directe de signaux d'entrée faibles (niveau de bruit non nul) peut améliorer la détection des signaux sensorimoteurs, qui sont bénéfiques à la performance des tâches motrices (e.g. tâches d'équilibre) (Woo et al., 2017). De même, les sujets blessés sont plus sensibles à l'ajout d'informations tactiles que les sujets sains (Kuster et al., 1999). La détérioration des structures ligamentaires due à une entorse du genou entraîne une baisse de la proprioception du membre lésé qui peut être partiellement compensée par le port de CG (Ghai et al., 2018).

De prime abord, il semblerait que les effets du port de CG suivent une relation en forme de « U » selon la typologie des sujets. Les sujets présentant un contrôle postural déficient semblent être plus réceptifs aux informations supplémentaires apportées par le port de CG que les individus dont le contrôle postural n'a pas été affecté par le vieillissement ou des blessures (Hijmans et al., 2009). Certaines études sur les effets de différentes modalités de stimulation des récepteurs cutanés ont montré qu'il existait une grande variabilité des réponses des individus (Pavailler et al., 2016; Rogers et al., 2001; You et al., 2004). Les sujets ayant une faible acuité proprioceptive semblent répondre plus favorablement aux dispositifs de stimulation tactile. Néanmoins, aucune étude ne s'est spécifiquement intéressée aux différences interindividuelles associées au port de vêtements de compression sur le contrôle postural de sujets jeunes avec ou sans expertise sportive particulière

2.1. Stimulation du contrôle postural de sujets jeunes en bonne santé

Nous avons analysé les effets des CG sur le contrôle postural de sujets jeunes et sains en s'intéressant aux différences interindividuelles. Si les études avec les personnes âgées sont nombreuses (Hijmans et al., 2009; Jaakkola et al., 2017; Woo et al., 2018, 2014), ce n'est pas le cas avec les sujets jeunes en bonne santé. Une seule étude a analysé les effets des vêtements de compression sur le contrôle postural chez cette population et aucun effet significatif attribuable aux CG n'a été relevé (Hijmans et al., 2009). Dans cette étude, deux groupes de sujets ont été recrutés (un groupe de sujets âgés et un groupe de sujets sains). Les sujets ont été

stimulés par une compression appliquée aux chevilles et aux pieds à l'aide de bas de compression médicaux. Il est fort probable que la partie de la chaussette comprenant le pied ait pu perturber les récepteurs cutanés plantaires et ne pas laisser apparaître d'effet positif chez les sujets jeunes. De plus, cela pourrait expliquer que le contrôle postural des sujets âgés ait été détérioré dans la condition expérimentale.

Dans la présente étude, l'analyse statistique réalisée à l'échelle global de l'échantillon n'a pas montré de différence significative entre la condition de référence (sans CG) et expérimentale (avec CG) sur le contrôle de l'équilibre. Les études précédentes sur les effets des vêtements qui interagissent avec les mécanorécepteurs de la peau, tels que les vêtements de compression, les orthèses de cheville et les bandes adhésives, ont également produit des résultats concordants chez des sujets jeunes, en bonne santé et non blessés, ainsi que chez des sportifs amateurs (Cavanaugh et al., 2016; Inglés et al., 2019; Jaakkola et al., 2017; Medeiros Barbosa et al., 2019; Papadopoulos et al., 2007; Willeford et al., 2018).

Nous avons donc réalisé une classification hiérarchique en clusters pour appréhender l'hétérogénéité des réponses observées au sein de l'échantillon (Pellegrini, et al. 2018). L'analyse en cluster a ainsi permis d'identifier plusieurs sous-groupes de sujets au sein de l'échantillon de participants et de mettre en évidence une grande diversité de réponses individuelles au port de CG. Les sous-groupes ont été différenciés en fonction de la capacité initiale d'équilibration des participants et de leur capacité à bénéficier ou non du port de CG pour améliorer le contrôle de l'équilibre. Dans les deux tâches posturales testées (support stable et instable), seuls les individus qui présentaient les valeurs les plus élevées des paramètres linéaires du centre de pression dans la condition de référence (e.g. avec un contrôle de l'équilibre moins efficace ou plus exploratoire comparativement aux autres sujets) ont profité du port des CG pour améliorer leur contrôle de l'équilibre. Au contraire, les individus qui présentaient un contrôle de l'équilibre efficace au départ (ou moins exploratoire), caractérisé notamment par des valeurs peu élevées de paramètres linéaires du centre de pression, n'ont pas profité du port de vêtements de compression pour améliorer leur équilibre.

Ce résultat est cohérent avec certaines études sur l'influence des dispositifs externes qui stimulent les mécanorécepteurs cutanés sur le contrôle de l'équilibre qui ont rapporté une grande variabilité interindividuelle dans les réponses à la stimulation cutanée au sein d'un groupe homogène de jeunes sains (Broatch et al., 2021; Pavailler et al., 2016; Rogers et al., 2001; You et al., 2004). Dans leur étude, Pavailler et al. (2016) ont identifié deux principales tactiques sensorimotrices préférées qui peuvent expliquer cette variabilité interindividuelle. Certains sujets, dits dépendants du support, s'appuient davantage sur l'exploitation de la géométrie de la

surface d'appui en tant que cadre de référence en attribuant un poids élevé aux signaux somatosensoriels provenant des mécanorécepteurs proprioceptifs de la cheville et des mécanorécepteurs cutanés plantaires. D'autres sujets, dits dépendants de la gravité, se fient davantage aux signaux liés à la détection de la gravité en attribuant un poids élevé aux signaux vestibulaires. Chaque individu attribue un poids différent à chaque modalité sensorielle disponible selon sa stratégie sensorimotrice préférentielle (Pavailler et al., 2016). Il est possible que les sujets de la présente étude aient réagi à la stimulation tactile en fonction de leur stratégie sensorielle préférentielle (dépendant du support ou de la gravité). Les sujets avec des valeurs élevées des paramètres linéaires du CP en condition de référence présentaient des caractéristiques typiques de sujets dépendants de la gravité en adoptant un comportement postural exploratoire afin d'obtenir des informations à partir de signaux graviceptifs (e.g. signaux vestibulaires) de manière plus efficace (Isableu & Vuillerme, 2006). Les individus caractérisés par de faibles valeurs des paramètres linéaires du CP au départ (e.g. avec un contrôle de l'équilibre moins exploratoire) étaient probablement dépendant du support et s'appuyaient certainement davantage sur les signaux proprioceptifs pour réguler leur équilibre. Seuls les sujets dépendants de la gravité ont pu tirer profit du port de manchons de compression. Il est possible que leur comportement postural plus exploratoire leur a permis de tirer profit des vêtements de compression. Avec un comportement postural exploratoire, des interactions plus importantes ont certainement eu lieu entre les mécanorécepteurs cutanés situés sous les vêtements de compression, facilitant ainsi la prise d'information sur les mouvements liés aux oscillations posturales (Yu et al. 2011). Cela peut expliquer pourquoi l'ajout de stimuli tactiles a entraîné une plus grande réduction des oscillations posturales chez ces sujets dépendants de la gravité comparativement aux sujets dépendants du support.

2.2. Stimulation du contrôle postural de sportifs experts

Nous avons analysé les effets aigus du port de vêtements de compression sur le contrôle postural chez des joueurs de handball professionnels. Seulement deux études avaient testé l'influence des CG sur le contrôle postural de sujets sportifs. Michael et al. (2014) ont montré que le port de tels dispositifs pouvait améliorer le contrôle postural des porteurs tandis que Sperlich et al. (2013) n'ont signalé aucun effet bénéfique dans un groupe de skieurs alpins de haut niveau. Ainsi la question d'un potentiel effet de CG sur le contrôle postural des sportifs reste ouverte. Nous avons émis l'hypothèse que le port de CG améliorerait le contrôle postural des joueurs de handball professionnels.

Dans la présente étude, les résultats issus d'une analyse statistique classique réalisée sur l'ensemble de l'échantillon n'ont pas permis de mettre en évidence un bénéfice lié au port de vêtements de compression. Cependant, les résultats de la littérature concernant la stimulation des membres inférieurs par des dispositifs tactiles (par exemple, les CG, les rubans adhésifs et les bandes de kinésiologie) montrent une influence plutôt positive sur le contrôle de l'équilibre lorsque les informations somatosensorielles sont modifiées par des manipulations expérimentales contraignantes (par exemple lorsque la vision est occultée) (Lopes et al., 2014; Michael et al., 2014; Woo et al., 2018; You et al., 2004). Or dans la présente étude nous avons évalué le contrôle postural des sujets dans une condition posturale dynamique sans contrainte visuelle. L'effet des CG est par ailleurs limité lorsque les sujets sont debout sur des supports instables (planche d'équilibre comme dans la présente étude) ou lors de l'exécution de tâches dynamiques (test d'équilibre en Y), probablement en raison de la disponibilité de repères visuels et de la contribution accrue des afférences vestibulaires et proprioceptives en raison de mouvements articulaires plus importants, ce qui pourrait avoir limité la pondération des indices somatosensoriels supplémentaires fournis par la CG (Peterka, 2018, 2002).

Dans un second temps nous avons utilisé une méthode de classification par regroupement hiérarchique qui nous a permis d'identifier deux sous-groupes distincts et homogènes de participants présentant des caractéristiques spécifiques et répondant de manière différente au port de CG, illustrant ainsi une grande variabilité interindividuelle dans la capacité à tirer profit du port de CG pour améliorer le contrôle de l'équilibre. Le premier sous-groupe regroupait des individus qui présentaient de faibles valeurs de paramètres linéaires du CP en condition de référence, caractéristiques d'un contrôle postural globalement performant. Le second sous-groupe regroupait des participants qui présentaient des valeurs relativement élevées de paramètres linéaires de CP, caractéristiques d'un contrôle postural moins performant comparativement aux sujets du premier sous-groupe (Paillard & Noé, 2015). Or, seuls les sujets du premier sous-groupe ont bénéficié du port des CG pour améliorer leur contrôle de l'équilibre. Les individus du premier sous-groupe ont ainsi montré une plus grande sensibilité à la manipulation somatosensorielle en étant les seuls participants à profiter des CG pour améliorer le contrôle de l'équilibre. Ces sportifs de haut niveau avec un contrôle de l'équilibre particulièrement performant ont certainement développé par leur pratique une capacité de repondération sensorielle optimale (Paillard, 2017), qui, leur a permis de bénéficier du port des CG pour améliorer le contrôle de leur équilibre.

2.3. Asymétrie du contrôle postural inter-membres

L'objectif de cette étude était d'analyser les effets du port de CG sur les asymétries d'équilibre inter-membres. La présence d'asymétrie inter-membre peut être un prédicteur fiable des blessures chez les sportifs (Marchetti et al., 2014; Promsri et al., 2018). Or nous savons que les dispositifs compressifs peuvent améliorer la précision du mouvement en optimisant notamment l'acuité proprioceptive (Woo et al., 2021). Nous avons donc émis l'hypothèse selon laquelle le port de CG réduirait les asymétries d'équilibre entre les membres, en particulier chez les sujets présentant un niveau élevé d'asymétries. Nous avons sélectionné des sujets sportifs pratiquant le handball qui est considéré comme un sport dit « asymétrique » (Marchetti et al., 2014; Paillard & Noé, 2020; Pau et al., 2021). Cette pratique entraîne une sollicitation récurrente qui diffère entre le côté non dominant et dominant et prédispose les joueurs à présenter des asymétries d'équilibre inter-membres (Marchetti et al., 2014; Paillard and Noé, 2020).

L'asymétrie inter-membre des participants a été caractérisée par un indice d'asymétrie appliqué à chaque paramètre du CP (Fort-Vanmeerhaeghe et al., 2020; Read et al., 2018). L'objectif était de pouvoir identifier les participants qui bénéficiaient du port de CG pour réduire les asymétries d'équilibre entre les membres et ceux qui n'en bénéficiaient pas. Une analyse qualitative (méthode de dichotomisation) a également été réalisée afin de caractériser l'influence spécifique des CG sur le contrôle postural de la jambe dominante et non dominante. Trois niveaux d'influence du CG ont été choisis : une influence négative, une influence négligeable et une influence positive.

L'approche statistique standard avec des comparaisons entre les conditions de référence et expérimentales a montré que le port de CG n'était pas associé à une réduction significative des asymétries de l'équilibre inter-membres. Par la suite, nous avons réalisé une analyse des corrélations entre l'indice d'asymétrie dans la condition de référence et l'évolution de l'indice d'asymétrie entre les conditions expérimentales. Les résultats ont démontré que les effets bénéfiques des CG sur la réduction des asymétries du contrôle postural inter-membres étaient liés au niveau d'asymétrie des participants au départ. Seuls les participants présentant des niveaux élevés d'asymétries d'équilibre entre les membres au départ ont bénéficié des CG pour réduire les asymétries d'équilibre entre les membres. Ces résultats mettent à nouveau en exergue une hétérogénéité dans la capacité des participants à bénéficier du port des CG pour réduire les asymétries d'équilibre entre les membres. Les études précédentes sur les effets des CG sur les capacités somatosensorielles fonctionnelles ont produit des résultats concordants tout en mettant en évidence une forte variabilité interindividuelle des réponses chez les sujets jeunes et

sains (Broatch et al., 2021; Cameron et al., 2008; You et al., 2004). Ces études ont montré que seuls les participants ayant une faible capacité somatosensorielle des membres inférieurs bénéficiaient du port des CG pour améliorer la perception de la position articulaire, illustrant ainsi que l'ampleur des effets bénéfiques du port de la CG était inversement liée à la capacité somatosensorielle du participant au départ. Des résultats similaires ont été observés avec d'autres stratégies de stimulation telles que le taping de la cheville (Long et al., 2017), les semelles texturées (Steinberg et al., 2016) et la stimulation vibratoire (Liu et al., 2021).

Les asymétries d'équilibre entre les membres sont principalement liées à des différences de traitement somatosensoriel entre les deux jambes provenant d'une asymétrie hémisphérique cérébrale (Liu et al., 2021; Marcori et al., 2019; Promsri et al., 2019, 2018). Goble et al. (2006) rapportent que, chez les droitiers, le système bras/hémisphère non dominant est plus apte à utiliser les informations proprioceptives liées à la position que le système bras/hémisphère dominant. Par analogie, nous pouvons émettre l'hypothèse qu'un tel avantage pourrait refléter un rôle préférentiel du système jambe/hémisphère non dominant dans le maintien d'une posture unilatérale statique qui pourraient être nécessaires lors de tâches motrices comme frapper dans un ballon au football (Carnahan & Elliott, 1987; Goble et al., 2006; Hart et al., 2014). Les antécédents de blessures des participants et/ou leur expérience de pratiques motrices asymétriques peuvent moduler la latéralisation du contrôle de l'équilibre et augmenter la différence dans le traitement somatosensoriel entre les deux jambes, induisant ainsi de grandes différences interindividuelles d'asymétrie d'équilibre inter-membres (Marcori et al., 2019; Paillard & Noé, 2020). A titre d'exemple, la majorité des individus utilisent préférentiellement la jambe dominante pour effectuer des tâches motrices dynamiques (comme taper dans un ballon) tout en utilisant la jambe non dominante pour stabiliser la posture (Huurnink et al., 2014).

Dans la présente étude, les participants présentant des niveaux élevés d'asymétries d'équilibre entre les membres au départ ont bénéficié du port de CG pour réduire les asymétries d'équilibre entre les membres. Cependant, dans les tâches posturales stable et instable, les données de l'analyse qualitative concernant l'influence spécifique des CG sur les deux jambes n'ont pas illustré une influence plus forte des CG sur la jambe dominante ou la jambe non dominante chez les individus du sous-groupe asymétrique (c'est-à-dire les individus qui ont bénéficié du port de la CG pour réduire de façon marquée les asymétries entre les membres). Chez les participants présentant de faibles niveaux d'asymétries d'équilibre entre les membres au départ, le port de CG n'a pas été bénéfique et pouvait même augmenter les asymétries d'équilibre entre

les membres chez certains participants. D'autres études ont rapporté des résultats concordants en montrant que l'acuité proprioceptive pouvait diminuer chez les participants ayant des niveaux plus élevés de capacité proprioceptive lorsqu'ils portaient des dispositifs externes qui stimulaient les récepteurs cutanés (Cameron et al., 2008; Liu et al., 2021; Long et al., 2017; Steinberg et al., 2016). Ces auteurs ont postulé que chez les sujets ayant une acuité proprioceptive élevée au départ, l'application d'un dispositif de stimulation externe pouvait surcharger le système sensorimoteur en délivrant des informations redondantes, entraînant ainsi une altération de la capacité proprioceptive. Liu et al. (2021) ont remarqué que la proprioception se détériorait uniquement sur la jambe dominante chez les individus ayant une acuité proprioceptive élevée après la stimulation des muscles du mollet avec un rouleau en mousse vibrant. Nos résultats de l'analyse qualitative montrent également que, de manière générale, le port de CG avait un impact plus important sur la jambe dominante et, plus spécifiquement, que les CG n'influençaient négativement que la jambe dominante chez les individus chez qui le port de CG augmentait les asymétries inter membres. Nos résultats semblent donc confirmer l'hypothèse formulée par Liu et al. (2021) concernant les effets différents de l'application de stimuli externes sur les différents hémisphères et montrent que l'hémisphère non dominant serait moins sensible à la stimulation somatosensorielle.

3. Conclusion générale et perspectives

Ce travail de thèse a contribué à enrichir la littérature scientifique sur les effets aigus des vêtements de compression en apportant des preuves tangibles de l'impact de l'hétérogénéité des sujets dans les études expérimentales. Il a également permis de mettre en exergue les effets aigus de ces dispositifs sur les asymétries posturales inter-membres, sujet encore jamais traité à notre connaissance.

L'analyse des effets du port des vêtements de compression sur le contrôle postural a révélé des effets distincts selon le type de sujets considérés. Cette hétérogénéité dans la capacité des participants à bénéficier du port de CG pour améliorer le contrôle de l'équilibre pourrait expliquer les résultats controversés concernant l'influence des vêtements de compression sur le contrôle de l'équilibre. La capacité à tirer profit des dispositifs tactiles qui stimulent les récepteurs cutanés tels que les CG pour améliorer le contrôle de l'équilibre semble décrire une relation en forme de U en fonction de l'âge et des capacités d'équilibre et/ou proprioceptives des sujets. Des effets bénéfiques ont été rapportés chez les personnes ayant une faible acuité proprioceptive et/ou une faible capacité d'équilibration (individus âgés, blessés) et chez les personnes ayant une bonne acuité proprioceptive et/ou un bon équilibre (athlètes) (Kuster et al.,

1999; Michael et al., 2014; Palm et al., 2012; Woo et al., 2018). Dans la présente étude, les résultats chez une population saine en bonne santé ou sportive laissent à penser qu'il existe une grande hétérogénéité même dans des groupes à priori fortement homogènes (groupe sportif). La relation en forme de U que nous évoquions précédemment serait donc davantage liée aux capacités d'équilibre intrinsèques et/ou proprioceptives des sujets et de leur capacité à tirer profit de la stimulation tactile plutôt qu'à l'âge ou du niveau d'expertise des sujets. Il est aussi envisageable que le seuil des mécanorécepteurs diffère entre chaque participant de par l'utilisation préférentielle de certaines stratégies sensorielles (Pavailler et al., 2016). Nous pouvons émettre l'hypothèse que la sollicitation régulière d'une stratégie par rapport à une autre puisse entraîner une plasticité neuronale qui facilite l'intégration de la voie sensorielle la plus souvent sollicitée. Si l'on prend pour exemple les sportifs de haut niveau, il est possible qu'une stratégie préférentielle les poussent constamment à privilégier les afférences somatosensorielles conduisant à des adaptations structurelles et fonctionnelles de la fonction posturale (Han et al., 2015; Paillard, 2019, 2017; Perrin et al., 2002).

L'efficacité des CG peut également dépendre de la pression qu'ils exercent sur la peau. Selon le modèle de CG, la pression exercée n'est pas identique et n'a donc pas les mêmes effets. Les niveaux de compression standard pour les bas de compression sont de 15-20 mmHg (subclinique), 20-30 mmHg (classe médicale 1), 30-40 mmHg (classe médicale 2) et 40-50 mmHg (classe médicale 3). Il existe des modèles progressifs et dégressifs qui se traduisent par une forte compression au niveau du mollet qui se réduit progressivement au niveau de la cheville et inversement de façon réciproque. Il semblerait qu'une compression trop faible ou trop élevée n'ait pas d'effet significatif sur le contrôle postural (Jaakkola et al., 2017; Reich-Schupke et al., 2016; Woo et al., 2018). Le phénomène de résonance stochastique pourrait expliquer ces résultats. Avec un ajout de bruit approprié appliqué au signal sensoriel, les stimuli peuvent être détectés plus facilement, puisque les seuils d'activation des récepteurs sensoriels sont diminués. Dans le cas d'une compression trop élevée, cela pourrait saturer le système qui ne pourrait plus exploiter le bruit induit (Davids, 2004; Woo et al., 2017). La pression appliquée par les vêtements de compression est une variable rarement prise en compte dans la littérature. Les prochaines études devront donc envisager de mesurer la pression exercée par les CG. Aussi, compte tenu de l'hétérogénéité des réponses à la stimulation tactile il semble pertinent d'analyser les préférences sensorimotrices des sujets avant d'analyser les effets que peuvent avoir les CG sur leur contrôle postural.

D'un point de vue pratique, les résultats suggèrent que le port de CG pourrait améliorer le contrôle postural de certains sujets en bonne santé et sportifs sans avoir d'effets délétères pour les sujets qui ne tireraient pas profit de la stimulation tactile. Les vêtements de compression pourraient donc avoir un effet prophylactique et prévenir les blessures tout en réduisant les asymétries de contrôle postural inter-membres. Néanmoins si cela s'avère vrai pour les participants présentant des niveaux élevés d'asymétries d'équilibre inter-membres, ce n'est pas le cas pour les participants présentant de faibles asymétries d'équilibre dont le port de CG devrait être évité chez ces participants.

Partie IV – Bibliographie

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Partie V Annexe



Effects of Compression Garments on Balance Control in Young Healthy Active Subjects: A Hierarchical Cluster Analysis

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There is controversy about the influence of compression garments on balance control. A positive influence was reported in elderly and injured individuals, whereas no beneficial effects were observed in young healthy active subjects, which is likely due to the large inter-individual differences in these subjects. Hence, this study investigated the acute effects of compression garments on balance control in young healthy active subjects by addressing the issue of heterogeneity of individuals' responses to the wearing of compression garments. Thirteen young, healthy, active subjects were recruited. They stood on a force plate which recorded the center of foot pressure displacements in a monopodal stance with the eyes closed and on a wobble board with the eyes open, while wearing compression garments or not. Statistics were first calculated with the data from the whole sample. A hierarchical cluster analysis was also performed in order to categorize the participants' behaviors into subgroups with similar characteristics. The whole group analysis showed that there were no significant effects attributed to compression garments. The clustering analysis identified distinct and homogeneous subgroups of participants. Only participants who swayed the more at baseline benefited from the wearing of compression garments to improve their balance control. These participants might have either a gravity-dependent preferred sensorimotor strategy with an exploratory postural behavior or poorer balance/proprioceptive abilities. Since poor balance control is a predictor of sports injury risk, wearing compression garments during sports practice could be viewed as a potential prevention strategy for individuals at risk.

Keywords: sports, posture, postural balance, sensorimotor control, sensory reweighting

INTRODUCTION

The somatosensory system highly contributes to balance control. It provides information about body movements that lead to small-sized tissue deformation and activation of cutaneous, muscle, and articular mechanoreceptors (Krishnamoorthy et al., 2002). From an ecological perspective (Gibson, 1966), the somatosensory system should not be reduced to the mere consideration of nerve cells (i.e., mechanoreceptors): it should be considered at a more expansive scale while integrating nerve, muscle, and connective tissue cells in a complex tensegrity assemblage (Palatinus et al., 2014;

Turvey and Fonseca, 2014). Connective tissue is of particular importance since it has a uniting function by binding every cell to its neighbors in order to form a whole medium that enables the transmission and the distribution of mechanical forces within the tensegrity assemblage (Palatinus et al., 2014; Turvey and Fonseca, 2014). Such a unification gives emphasis of relations between individual cells, which facilitate the pickup of information about body motion that emerges from interactions between perception, action, information, and task goal (Riley et al., 1999). In this context, the wearing of compression garments may change the tension–compression relations in the tensegrity assemblage. Actually, the overall constriction provided by compression garments acts as a mechanically supportive framework sensitive to body movements that can activate interacting cutaneous mechanoreceptors that individually would not have been activated. Hence, compression garments can enhance the perception of somatosensory information and influence balance control positively by reducing body sway during quiet standing (Kuster et al., 1999; Michael et al., 2014; Woo et al., 2017, 2018).

These beneficial effects of compression garments on balance control would be most pronounced among elderly and injured subjects (Kuster et al., 1999; You et al., 2004; Palm et al., 2012; Woo et al., 2018) and high-level athletes (Michael et al., 2014). These results suggest that only subjects with either sensory deficits, such as elderly and injured subjects, or exceptional sensory acuity and/or sensory reweighting mechanisms, such as high-level athletes (Paillard, 2017, 2019), would be able to benefit from compression garments to improve balance control. By comparison, “ordinary” active subjects such as young, healthy, non-injured subjects and non-elite/recreational athletes would not benefit from compression garments to improve balance control (Hijmans et al., 2009; Cavanaugh et al., 2016; Jaakkola et al., 2017).

Further studies about the influence of external devices that stimulate cutaneous receptors have shown that there was a great variability between individuals’ responses to cutaneous stimulation (Rogers et al., 2001; You et al., 2004; Pavailler et al., 2016). Hence, one can assume that the effects of compression garments on balance control would be subject-dependent in active subjects. This could explain the absence of a significant effect as reported by studies about the influence of compression garments on balance control in active subjects (Hijmans et al., 2009; Cavanaugh et al., 2016; Jaakkola et al., 2017). Actually, these studies were performed with standard group ensemble average statistical approaches that do not allow to specifically address the issue of heterogeneity of individuals’ postural behavior to the wearing of compression garments.

The purpose of this study was therefore to investigate the effects of compression garments on balance control in young, healthy, active subjects by addressing the issue of inter-individual variability in the ability to take advantage of compression garments to improve balance control. To this end, a hierarchical cluster analysis was performed. The clustering analysis is a multivariate statistical method which categorizes the participants’ behaviors into subgroups with similar characteristics, thus facilitating the investigation of differences in individual responses

by enabling the identification of natural groupings that may exist in a whole sample (Watelain et al., 2000; White and McNair, 2002). It was hypothesized that the wearing of compression garments differently affected balance control in active subjects.

MATERIALS AND METHODS

Participants

Thirteen male young, healthy, active subjects having recreational handball practice (age: 27.9 ± 8.36 years old, height: 178.6 ± 7.89 cm; body mass: 79.62 ± 14.28 kg; training hour per week: 3 h; mean \pm SD) participated voluntarily in the experiment. The exclusion criteria included any neuromuscular impairments and/or ankle, knee, and hip trauma in the past 2 years and medication that might influence balance. The participants were also asked to avoid strenuous activity and the ingestion of alcohol or/and excitatory substances 24 h before the experimental session. All the participants voluntarily signed an informed consent before starting the experiment, which was in accordance with the Declaration of Helsinki. All procedures were approved by and performed in accordance with the relevant guidelines and regulations of the University of Pau and Adour Countries Ethics Committee.

Apparatus and Procedure

The participants were asked to sway and move as little as possible when standing barefoot in a monopodal stance on their non-dominant leg (i.e., the supporting leg, which was determined as the leg which is not used to kick a ball) for 25 s on a force platform (Stabilotest® Techno Concept™, Mane, France) which sampled the center of foot pressure displacements at 40 Hz. Two postural tasks were conducted in a counterbalanced order: a stable task where the participants stood on stable ground with the eyes closed (while keeping their gaze straight ahead) and an unstable task where they stood on a wobble board with a diameter of 40 cm and a height of 8 cm (Balance-board, Sissel® GmbH, Bad Dürkheim, Germany) with the eyes open (while looking at a fixed-level target at a distance of 2 m). These postural tasks were chosen because tactile cues provided by a light touch or by garments that stimulate cutaneous receptors are more effective in conditions of increased sway, i.e., when standing on an unstable surface and/or when a sensory pathway critical for standing posture is perturbed (e.g., when vision is occluded) (Rogers et al., 2001; Michael et al., 2014; Woo et al., 2018). For accurate and similar feet positioning between all subjects, the foot was placed according to precise landmarks on the force platform and the wobble board. All postural tasks were performed with or without wearing compression garments (COMP and REF condition respectively). In the COMP condition, calf compression sleeves (Booster, BV sport®, Saint Etienne, France) made of 69% polyamide, 21% elastane, and 10% yarn were worn by the participants. The pressure was 0 mmHg at the ankle, 20 mmHg at the external spinning, and 25 mmHg at the internal spinning of the calf. In order to avoid any learning effect, the participants had to perform a familiarization session before data acquisition while performing two trials in each postural task

(Cug and Wikstrom, 2014). Center of pressure (COP) surface area (S: 90% confidence ellipse), mean center of pressure velocity along the medio-lateral (VX), and antero-posterior (VY) axes were calculated as linear measures characterizing balance control and postural sway; within the framework of a quiet stance paradigm, the lower these parameters, the lower amount of postural sway and the more efficient the balance control (Paillard and Noé, 2015). The analysis of the dynamical features of postural sway variations was calculated from the sample entropy (SampEn). Sample entropy was calculated from the resultant COP velocity using the method proposed by Ramdani et al. (2009), with $m = 3$ and $r = 0.2$. SampEn provides information about the regulation processes involved in balance control and attention investment. Low SampEn values characterize repetitive patterns of sway movements and reflect a strong cognitive contribution to balance control with reduced adaptive abilities. High SampEn values are indicative of a more automatic and adaptive control of balance (Ramdani et al., 2009; Vaillancourt and Newell, 2002). The relative difference of each center of pressure parameter between both conditions [relative difference = $100 \times (\text{COMP} - \text{REF})/\text{REF}$] was also calculated. Relative difference is an easily interpretable descriptor, which limits the influence of the heterogeneity between participants in the REF condition and makes it easy to differentiate participants who benefit from CG wearing (negative value of relative difference of linear center of pressure metrics and positive value of relative difference of SampEn) and those who do not (positive value of relative difference of linear center of pressure metrics and negative value of relative difference of SampEn).

Statistical Analysis

Data were analyzed in two steps. The first step consisted of analyzing the influence of experimental conditions (REF and COMP) on dependent variables (S, VX, VY and SampEn) with a standard group ensemble average method (whole group analysis). Normality was tested using Shapiro–Wilk test. As the dependent variables did not meet the assumption of normal distribution, non-parametric Wilcoxon signed-rank tests were applied to determine differences between the REF and the COMP conditions in terms of the relevant dependent variable.

A hierarchical cluster analysis was performed in a second step to classify the participants' behavior into subgroups with similar characteristics (Watelain et al., 2000; White and McNair, 2002). A normalized principal component analysis was first used to reduce the dimensionality of the data prior to performing the hierarchical cluster analysis based on the five first principal component scores. COP parameters in the REF condition (S, VX, VY, and SampEn) and the relative differences (RD) of each COP parameter (RD_S, RD_VX, RD_VY, and RD_SampEn) between both conditions were used to produce a 13×8 input matrix for the PCA [13 (number of participants) \times 8 (input variables)]. Once the number of clusters was identified, univariate tests were performed on dependent variables to determine which parameters best determine the cluster placement due to a significant difference from whole group mean (Lê et al., 2008). The stable and the unstable postural tasks were analyzed independently as two separated datasets. Statistical analyses were

performed with R statistical software using FactoMineR Package (Lê et al., 2008). The significance level was set at $p < 0.05$.

RESULTS

Table 1 illustrates the mean values of the center of pressure parameters in the whole sample with the characteristics of each cluster. When inferential statistics were conducted on the whole group, no significant differences were observed between REF and COMP conditions in both the stable and the unstable postural tasks.

In the stable postural task, the principal component analysis resulted in two components that explained 68.5% of the total variance of the original dataset. The first principal component accounted for 48.2% of the total variance. Among the variables that loaded this component, S_REF, VX_REF, and VY_REF were positively correlated, whereas RD_S and RD_VY were negatively correlated (**Figure 1A**). The second principal component explained 20.3% of the total variance and was mainly loaded with two variables, RD_VY and RD_SampEn, that were positively correlated. **Figure 1B** illustrates the individuals' factor map with the results from the hierarchical cluster analysis. Two clusters were identified with a heterogeneous distribution of individuals among the clusters (cluster 1, $n = 10$; cluster 2, $n = 3$). The center of pressure parameters that best determined group placement was acting on the first principal component axis (S_REF, VX_REF, VY_REF, RD_S, and RD_VY). Individuals from cluster 1 had low values of linear center of pressure metrics in the REF condition (S_REF, VX_REF, and VY_REF) and positive values of relative difference between both conditions (RD_S and RD_VY). Individuals from cluster 2 had high values of linear center of pressure metrics in the REF condition and negative values of relative difference.

In the unstable postural task, we left out participant number 7 from the analysis. As illustrated in **Figure 2B**, he was identified as an outlier on several dependent variables of the initial dataset (VY_REF, S_REF), which influenced the construction of the space too significantly. Participant number 7 was entered as an illustrative individual, and 12 active individuals were included in the principal component analysis and cluster analyses. The principal component analysis resulted in two components that explained 60.6% of the total variance of the original dataset. The first principal component accounted for 36.2% of the total variance and was mainly loaded with four variables: RD_S and RD_VY that were positively correlated and VX_REF and VY_REF which were acting in the opposite direction. The second principal component explained 24.3% of the total variance and was mainly loaded with five variables: RD_S, RD_VX, VY_REF, and SampEn REF that were positively correlated and RD_SampEn which was acting in the opposite direction (**Figure 2A**). Three clusters were identified with a fairly homogeneous distribution of individuals among the clusters (cluster 1, $n = 4$; cluster 2, $n = 3$, cluster 3, $n = 5$). The COP parameters that best determined group placement were acting on the PC1 axis (S_REF, VX_REF, VY_REF, RD_S, and RD_VY). Individuals from cluster 1 differed from the whole group by

TABLE 1 | Center of pressure (COP) parameters of the whole group with cluster characteristics in the different postural tasks and experimental conditions.

			<i>n</i>	REF	COMP	RD (%)
Stable task	S (mm ²)	Whole group	13	2,007.48 (1,120.31)	1,865.7 (801.08)	8.04 (43.41)
		Cluster 1	10	1,506.21 (580.01) ^a	1,807.212 (815.42)	22.67 (35.66) ^a
		Cluster 2	3	3,678.40 (756.58) ^a	2,060.50 (885.60)	-40.75 (30.72) ^a
	VX (mm s ⁻¹)	Whole group	13	65.07 (16.61)	64.55 (18.07)	-0.13 (14.54)
		Cluster 1	10	57.96 (10.25) ^a	58.3 (12.87)	1.11 (14.73)
		Cluster 2	3	88.76 (9.32) ^a	85.38 (19.17)	-4.28 (16.09)
	VY (mm s ⁻¹)	Whole group	13	52.51 (18.5)	51.73 (16.99)	3.70 (32.27)
		Cluster 1	10	43.52 (7.58) ^a	49.74 (17.77)	13.71 (29.33) ^a
		Cluster 2	3	82.47 (6.51) ^a	58.37 (14.99)	-29.68 (14.37) ^a
	SampEn	Whole group	13	1.26 (0.18)	1.26 (0.22)	0.37 (12.04)
		Cluster 1	10	1.24 (0.19)	1.23 (0.23)	-0.56 (13.73)
		Cluster 2	3	1.31 (0.20)	1.35 (0.16)	4.00 (4.81)
Unstable task	S (mm ²)	Whole group	13	700.55 (384.28)	693.70 (266.23)	6.96 (29.87)
		Cluster 1	4	619.50 (101.37)	538.83 (95.28)	-13.02 (8.03) ^a
		Cluster 2	3	679.70 (344.44)	874.23 (375.62)	32.30 (24.16)
		Cluster 3	5	558.74 (209.10)	608.32 (118.46)	15.77 (30.88)
	VX (mm s ⁻¹)	Whole group	13	41.04 (11.70)	39.15 (8.53)	-0.75 (23.71)
		Cluster 1	4	47.38 (6.43) ^a	38.53 (3.87)	-18.24 (5.97) ^a
		Cluster 2	3	34.95 (8.72)	44.79 (14.95)	26.60 (13.41) ^a
		Cluster 3	5	33.90 (2.15)	34.94 (6.17)	3.54 (19.96)
	VY (mm s ⁻¹)	Whole group	13	26.83 (8.49)	26.34 (5.68)	1.01 (12.73)
		Cluster 1	4	28.93 (4.39)	26.63 (2.6)	-7.14 (10.50) ^a
		Cluster 2	3	29.40 (5.48)	30.13 (4.19)	3.16 (5.76)
		Cluster 3	5	19.46 (1.70) ^a	21.51 (2.97)	10.42 (9.86)
	SampEn	Whole group	13	1.34 (0.22)	1.39 (0.18)	4.71 (9.93)
		Cluster 1	4	1.34 (0.10)	1.37 (0.17)	2.52 (9.3)
		Cluster 2	3	1.59 (0.24) ^a	1.56 (0.15)	-1.04 (10.07)
		Cluster 3	5	1.17 (0.14) ^a	1.30 (0.19)	11.01 (9.62)

Data are expressed as mean (SD).

S, COP surface area; VX and VY, mean COP velocity along the medio-lateral and antero-posterior axes, respectively; SampEn, sample entropy; *n*, frequencies for the whole group and subgroups; REF, reference condition; COMP, compression garments condition; RD, relative difference between both conditions [RD = 100 × (COMP - REF)/REF].

^aVariable identified as determinant of cluster placement due to a significant difference from the whole group mean ($p < 0.05$).

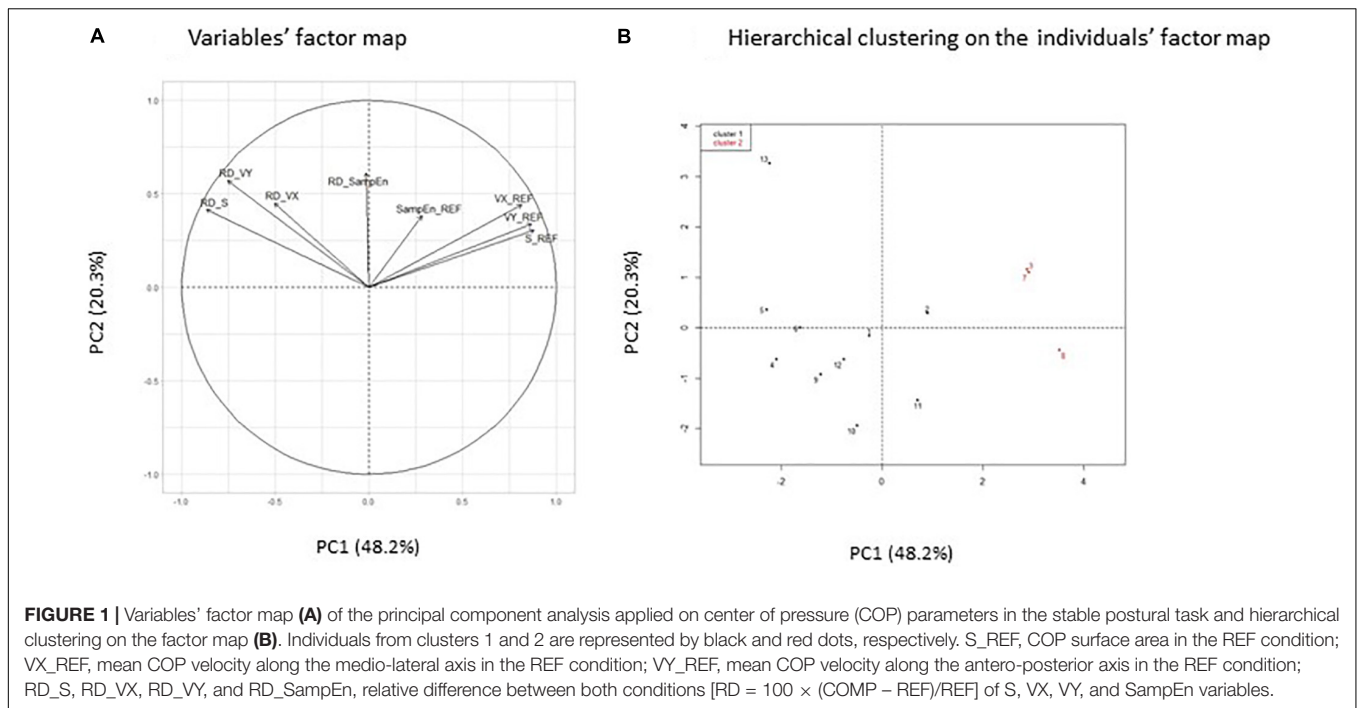
having higher values of VX_REF and lower values of RD_VX and RD_VY. Individuals from cluster 2 had higher values of SampEn_REF and RD_VX than those of the whole group. Finally, individuals from cluster 3 had lower values of SampEn_REF and VY_REF than those of the whole group (**Figure 2C** and **Table 1**).

DISCUSSION

The aim was to determine whether wearing of compression garments results in high variability between individuals' responses among a group of young, healthy, active subjects. The cluster analysis identified further distinct subgroups within the whole group of participants in each postural task, thus highlighting a large variation of individuals' responses to the wearing of compression garments. In both postural tasks, only individuals who exhibited the highest values of linear center of pressure parameters in the REF condition (i.e., the less efficient or the more exploratory balance control at baseline) benefited

from the wearing of compression garments to improve their balance control.

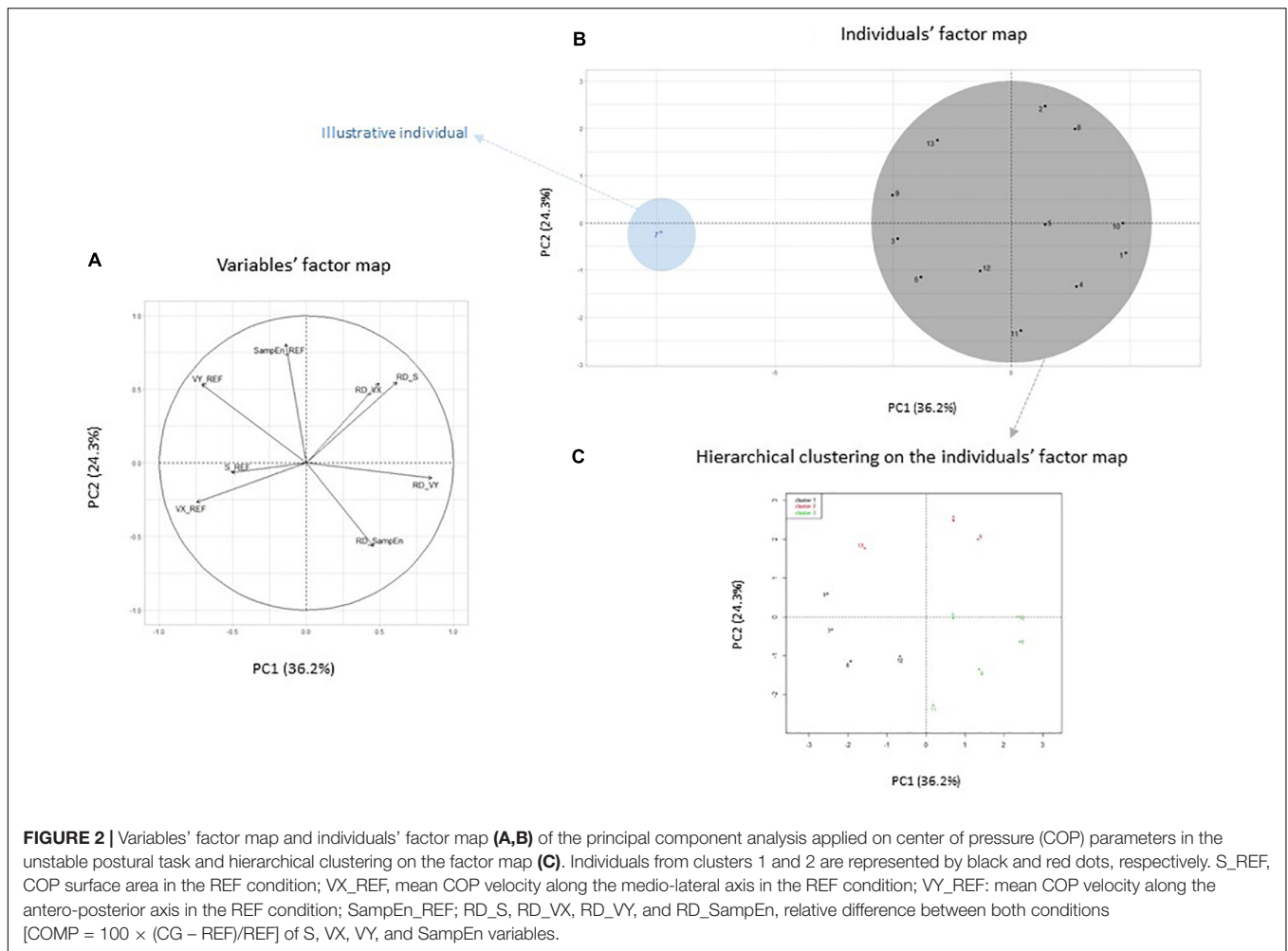
When statistics were performed on the whole group, our results showed that the wearing of compression garments did not significantly impact balance control. Previous studies about the effects of garments that interact with skin mechanoreceptors, such as compression garments, ankle braces, and taping, have also produced concordant findings with young, healthy, non-injured subjects and recreational sports people (Papadopoulos et al., 2007; Hijmans et al., 2009; Cavanaugh et al., 2016; Jaakkola et al., 2017; Willeford et al., 2018; Inglés et al., 2019; Medeiros Barbosa et al., 2019). Nevertheless, the clustering approach identified distinct subgroups of participants who responded differently to the wearing of compression garments. This result is consistent with some studies about the influence of external devices that stimulate skin mechanoreceptors on balance control, which have reported a high inter-individual variability in responses to cutaneous stimulation within a homogeneous group of young, healthy participants (Rogers et al., 2001; You et al., 2004; Pavaiiler et al., 2016). In both the stable and the unstable postural tasks, the



clusters were differentiated according to the participants' balance behavior at baseline and their ability to benefit—or not—from CG wearing to improve balance control. The participants who exhibited an efficient balance control at baseline, with low linear metrics of postural sway and/or high values of sample entropy at baseline (participants from cluster 1 in the stable task and from clusters 2 and 3 in the unstable postural task), did not take advantage from compression garments to improve their balance control. Only the participants who exhibited higher linear metrics of postural sway at baseline (participants from clusters 2 and 1 in the stable and the unstable postural task, respectively) benefited from the wearing of compression garments (illustrated by negative values of relative differences of linear center of pressure parameters between COMP and REF condition) to improve their balance control. Rogers et al. (2001) reported concordant findings while showing that the application of tactile stimuli benefited, to a larger extent, the subjects who swayed more during normal standing. These authors hypothesized that the subjects who swayed the most at baseline might present a moderate sensorimotor deficit, thus explaining why the addition of tactile stimuli led to a greater reduction in sway. Woo et al. (2017) formulated a similar hypothesis while postulating that the subjects with healthy postural control systems may not benefit from garments that interact with cutaneous receptors to enhance balance control. Further studies about the influence of external devices that stimulate cutaneous receptors (e.g., CG, ankle brace, and elastic bandages) on leg proprioception reported concordant findings when showing that the magnitude of the beneficial effects of cutaneous stimulation was inversely related to the participant's proprioceptive acuity at baseline (Perlau et al., 1995; You et al., 2004; Cameron et al., 2008). You et al. (2004) also showed that external skin stimulation improved balance control only in

subjects with low proprioceptive acuity. In the present study, we could therefore logically assert that the subjects who swayed the most benefited from the wearing of compression garments to improve their balance control because of a poorer balance control at baseline due to poorer lower limb proprioception.

Nevertheless, Pavailler et al. (2016) suggested that the ability to benefit from cutaneous stimulation provided by external supports was not only related to proprioceptive acuity but also to differences in how individuals weigh somatosensory cues for controlling their balance (i.e., differences in the preferred sensorimotor strategy). According to these authors, cutaneous stimulation would be of greater benefit to the subjects who rely more on gravito-inertial cues (gravity-dependent subjects) than on proprioceptive cues (support-dependent subjects). It is known that gravity-dependent subjects adopt an exploratory postural behavior while exhibiting larger postural sway to gain information from graviceptive signals (e.g., vestibular cues) more efficiently (Isableu and Vuillermé, 2006; Pavailler et al., 2016). Even though the subjects in the present study were asked to sway as little as possible in the context of a quiet stance paradigm, those who exhibited a greater postural sway could have a more exploratory postural behavior associated with a gravity-dependent sensorimotor strategy. However, exploratory movements have causal effects on the accuracy of affordance judgments (Stoffregen, 2003; Yu et al., 2011). Within the ecological approach to perception and action, the contents of perception are affordances (Gibson, 1966; Stoffregen, 2003). Affordances are neither properties of a subject nor properties of their environment, but they are emergent properties of the subject–environment system (Stoffregen, 2003). Compression garments act as a mechanically supportive framework which has a uniting function by nesting constricted mechanoreceptors, thus



offering the opportunity to facilitate the pickup of information about sway-related movements in order to comply with the steadiness instruction. Compression garments did not enhance somatosensory perception *per se*, and one should rather consider a subject wearing compression garments as a system that provides an affordance for reducing postural sway. Stoffregen (2003) stated that affordances are “what one can do, not what one must do,” which means that affordances are opportunities that are not necessarily exploited by subjects (Riley et al., 1999). Actually, the exploitation of affordances is intimately linked to the availability of body movements (Stoffregen, 2003). An affordance can be viewed as a hidden property of a system that would become meaningful when the system is subjected to movement. Yu et al. (2011) showed, for example, that a certain amount of body sway was necessary for the perception of affordances. In the present study, the accuracy of affordance perception might have been higher in the participants who swayed more at baseline, those who have a typical profile of support-dependent subjects. With a greater sway, greater interactions certainly occurred between the cutaneous mechanoreceptors located under the compression garments, thus facilitating the pickup of information about sway-related

movements. This could explain why only these subjects were able to take advantage from compression garments to reduce their postural sway.

This study showed that, among a sample of young, healthy, active subjects, only the participants who exhibited the higher amount of postural sway could benefit from the wearing of compression garments to comply with the steadiness instruction. Hence, it can be suggested that the ability to take advantage from the wearing of compression garments to improve balance control depends on the subjects' balance/proprioceptive abilities at baseline or preferred sensorimotor strategy. Further experiments are needed to explore how preferred sensorimotor strategy and balance/proprioceptive abilities influence the ability to take advantage of compression garments to improve balance control. From a practical point of view, knowing that poor balance control is a predictor of sports injury risk (Hrysomallis, 2011), subjects at higher risk of injury are likely to benefit from the wearing of compression garments. Hence, wearing compression garments during sports practice could be viewed as a cost-effective injury prevention strategy that would have a specific impact on individuals at risk without having any deleterious effects on other individuals.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by University of Pau and Adour Countries Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

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AUTHOR CONTRIBUTIONS

KB, FN, and TP designed the study. KB acquired the data. KB, FN, and NB analyzed the data. KB and FN wrote the manuscript. TP and NB revised the manuscript. All authors signed the final approval for publication.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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OPEN

Wearing compression garments differently affects monopodal postural balance in high-level athletes

Kévin Baige, Frédéric Noé & Thierry Paillard

This study investigated the acute effects of compression garments (CG) on balance control in elite athletes. 15 male professional handball players were recruited. They had to stand as motionless as possible in a monopodal stance on a force plate with the eyes closed and on a wobble board with the eyes open, while wearing CG or not. Centre of foot pressure mean velocity and surface area were calculated. Statistics were first calculated with the data from the whole sample. A hierarchical cluster analysis was also performed in order to categorize the participants' behaviours into subgroups with similar characteristics. The whole group analysis showed that there were no significant effects attributed to CG. The clustering analysis identified two distinct and homogeneous subgroups of participants. Only athletes with the best balance abilities at baseline could benefit from CG wearing to improve their balance control. These athletes, who swayed less and were more sensitive to somatosensory manipulation due to CG wearing, seem to control balance by adopting a support-dependent preferred sensorimotor tactic. Our findings suggest that amongst high-level athletes, the ability to benefit from CG wearing to improve balance control seems to depend on participants' intrinsic balance skills and/or preferred sensorimotor tactics.

Abbreviations

CG	Compression garments
COP	Centre of foot pressure
HCA	Hierarchical cluster analysis
PC	Principal component
PCA	Principal component analysis
RD	Relative difference ($RD = 100 * [CG - REF] / REF$)
REF	Reference
S	COP surface area
SD	Standard deviation
STA	Stable postural task with the eyes closed
UNSTA	Unstable postural task with the eyes open
VX	Mean COP velocity along the medio-lateral axis
VY	Mean COP velocity along the antero-posterior axis

Compression garments (CG) have been widely used in medicine in patients with venous disease, restricted mobility or with an immobilization of the lower limb for many years¹. CG create an external pressure gradient on the body surface which improves venous hemodynamics and prevents leg swelling and blood clots^{1,2}. The wearing of CG in sport has also become very popular during and after training or competition in order to improve physical performances³⁻⁵ and to accelerate recovery^{6,7}. Suggested mechanisms include attenuation of muscle oscillation during exercise^{4,5}, enhanced venous return, blood flow and muscle oxygenation with accelerated metabolic removal^{2,8}, reduced post-exercise edema⁹ and attenuated markers of muscle damage⁶. CG could have a beneficial influence on endurance exercise mainly by attenuating perceived exertion and muscle soreness and

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by improving running economy^{4,5}. CG could also affect neuromuscular performances such as vertical jumping and sprint performance. The exact mechanisms by which CG impact neuromuscular performances are not clear, but it may be due to the activation of cutaneous mechanoreceptors which elicits enhancements in the ability to perceive position in space and improves accuracy of motor actions such as jumping technique^{4,10,11}. The additional sensory cues from cutaneous mechanoreceptors provided by CG are also likely to improve movement control such as balance control^{12–16}.

When specifically focusing on the influence of CG on balance control, studies showed that CG did not bring any beneficial effect^{17–22}, whereas others showed that balance control was enhanced when wearing CG^{12,13,15,23,24}. The heterogeneity in these results might stem from participants characteristics (e.g., age, sex, healthy vs injured), conditions of balance control assessment (e.g. static vs dynamic postural tasks, monopodal vs bipodal stances, with eyes open or closed, on stable ground or unstable/compliant surface) and CG properties (segments/joints covered by the CG, level of compression). In general, CG rather induce beneficial effects when standing in monopodal stance^{12,13,23,24}, especially with the eyes closed^{12,13,24}. Only Woo et al. reported a positive influence of CG with a bipedal stance when assessing elderly participants who had to perform a Romberg test on a compliant surface¹⁵. CG seem to preferentially benefit to subjects with lower limb injuries^{12,23,24} than to non-injured subjects^{17–20}. The location of the compression (i.e. ankle, shank, knee or thigh) does not seem to be a major factor in explaining the differences observed in the studies. Some studies reported beneficial effects of CG on balance control with knee sleeves^{12,23}, socks¹⁵ and leggings¹³ whereas others did not report any beneficial effect with knee sleeves¹⁷ and socks^{18–20,22}. Similarly, the level of compression, which is not systematically specified in the studies, does not appear to be a major factor in explaining the heterogeneity of the results. Studies that have tested the effects of wearing CG of different compression levels reported that the level of compression had no influence on balance control^{15,19–22}.

Overall, CG would rather improve balance control in physically diminished/impaired subjects (e.g., elderly and injured) than in healthy young ones in particular in monopodal stance. Nonetheless, knowing that expertise in sport can enhance the process of sensory reweighting²⁵, expert athletes are likely to integrate more efficiently the cutaneous stimulation provided by CG to improve balance control. Only two studies, to our knowledge, have been conducted in order to test the influence of CG on balance control in sportspeople, while producing divergent findings^{13,22}. Michael et al. showed that balance control of sportswomen was improved when they wore CG¹³, whereas Sperlich et al. did not report any beneficial influence of CG in a group of competitive alpine skiers²². Nevertheless, Sperlich et al. performed a balance test with and without CG while asking participants to wear racing ski-boots²². These boots, which stimulate cutaneous mechanoreceptors in the foot and shank and provide a mechanically efficient support at the tibia level²⁶, might have acted as a confounding factor and hid a potential positive effect of CG. Hence the influence of expertise in sport on the ability to take advantage for CG to improve balance control remains an open question.

Consequently, this study was undertaken in order to investigate the acute effects of calf compression sleeves on monopodal balance control of professional elite handball players. It was hypothesized that calf compression sleeves would enhance monopodal balance control in professional handball players. Because of potential heterogeneity between participants' response to CG wearing, a normalized principal component analysis was used to reduce the dimensionality of the data before performing a hierarchical cluster analysis (HCA). The HCA is a multivariate statistical method which categorizes the participants' behaviours into subgroups with similar characteristics, thus facilitating the investigation of differences in individual responses by enabling the identification of natural groupings that may exist in a whole sample^{27,28}.

Results

Table 1 presents the mean values of COP parameters in the whole sample with the characteristics of each cluster. When inferential statistics were performed on the whole group, no significant differences were observed between REF and CG conditions in the STA postural task. Nevertheless, strong tendencies could be observed on VX and VY, which tended to be reduced in CG compared to the REF condition ($V = 92$; $P = 0.073$ and $V = 91$; $P = 0.083$). In the UNSTA postural task, no statistically significant differences or tendencies were observed between both conditions.

In the STA postural task, PCA resulted in two components that explained 70% of the total variance of the original dataset. PC1 accounted for 46.6% of the total variance and was loaded with three variables, RD_VY, RD_S and VY, which were positively correlated. PC2 explained 23.4% of the total variance and was loaded with three variables, S and VX, which were positively correlated, and RD_VX which was acting in the opposite direction (Fig. 1a). In the UNSTA postural task, PCA resulted in two components that explained 77.3% of the total variance of the original dataset. PC1 accounted for 54.0% of the total variance and was loaded with the three variables, VX, VY and RD_S, which were positively correlated. PC2 explained 23.3% of the total variance and was loaded with three variables, S and VY, which were positively correlated, and RD_VX which was acting in the opposite direction (Fig. 2a). In both postural tasks, the clustering analysis identified two clusters. The individuals' factor map (Figs. 1b and 2b) shows that there was a great variability between subjects and that individuals from these two clusters were mainly differentiated on the PC1 axis. Individuals from cluster 1 were located on the left side, with low values of postural parameters in the REF condition and negative values of relative difference between both conditions (Table 1). On the contrary, individuals from cluster 2 were located on the right side and had high values of postural parameters in the REF condition and positive values of relative difference between both conditions.

			n	REF	CG	RD
STA	S	Whole group	15	1,978.2 (536.3)	1,822.4 (736.7)	-7.9 (25.1)
		Cluster 1	8	1,725.8 (443.3)	1,281.3 (301.2)	-22.1 (22.6)
		Cluster 2	7	2,266.8 (509.8)	2,440.8 (569.1)	8.5 (17.0)
	VX	Whole group	15	59.4 (15.2)	54.8 (15.0) [§]	-7.2 (16.0)
		Cluster 1	8	52.3 (4.4)	44.9 (8.5)	-14.2 (14.2)
		Cluster 2	7	67.5 (19.3)	66.1 (12.9)	0.7 (15.1)
	VY	Whole group	15	46.7 (13.8)	43.1 (17.5) [§]	-9.7 (18.8)
		Cluster 1	8	38.7 (4.4)	30.0 (5.9)	-22.6 (12.7)
		Cluster 2	7	55.9 (15.3)	58.0 (13.5)	5.0 (12.7)
UNSTA	S	Whole group	15	707.0 (206.9)	648.7 (369.3)	-9.7 (38.8)
		Cluster 1	8	610.3 (130.6)	481.7 (201.2)	-21.3 (28.1)
		Cluster 2	7	817.5 (230.7)	839.6 (437.4)	3.5 (47.0)
	VX	Whole group	15	31.8 (12.2)	34.5 (17.7)	5.5 (16.9)
		Cluster 1	8	23.2 (6.6)	22.2 (5.1)	-2.9 (13.5)
		Cluster 2	7	41.6 (9.4)	48.6 (16.4)	15.1 (15.9)
	VY	Whole group	15	23.4 (7.1)	22.3 (7.7)	-5.3 (12.8)
		Cluster 1	8	18.5 (5.1)	16.1 (3.8)	-11.9 (8.9)
		Cluster 2	7	29.0 (4.2)	29.4 (3.5)	2.2 (12.9)

Table 1. COP parameters of the whole group with cluster characteristics in the different postural tasks and experimental conditions. Data are expressed as mean (SD). STA stable postural task with the eyes closed, UNSTA unstable postural task with the eyes open, REF reference condition, CG compression garments condition, S COP surface area, VX and VY mean COP velocity along the medio-lateral and antero-posterior axes respectively, RD relative difference between both conditions ($RD = 100 \cdot [CG - REF] / REF$). [§]illustrates a tendency from whole group statistics ($0.05 \leq P < 0.1$) between REF and CG conditions.

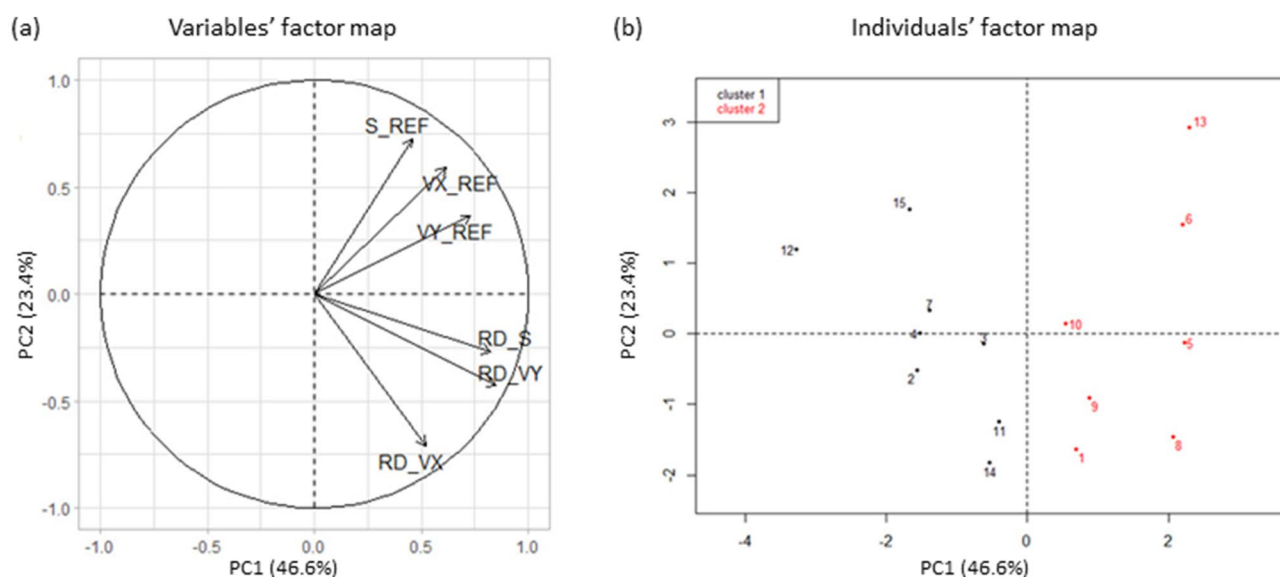


Figure 1. Variables' (a) and individuals' (b) factor map of the PCA applied on COP parameters in the STA postural task. Individuals from cluster 1 and 2 are represented by black and red dots respectively. S_REF COP surface area in the REF condition, VX_REF mean COP velocity along the medio-lateral axis in the REF condition, VY_REF mean COP velocity along the antero-posterior axis in the REF condition, RD_S , RD_VX and RD_VY relative difference between both conditions ($RD = 100 \cdot [CG - REF] / REF$) of S, VX and VY variables.

Discussion

The aim of this study was to analyze the acute effects of wearing CG on the monopodal balance control in elite professional handball players. When considering data from the whole sample, results from inferential statistics were not consistent with the hypothesis that CG would improve balance control, since the wearing of CG only induced tendencies to an improved monopodal balance control in the STA postural task. The HCA approach was successful in identifying two distinct and homogeneous subgroups of participants, thus illustrating that

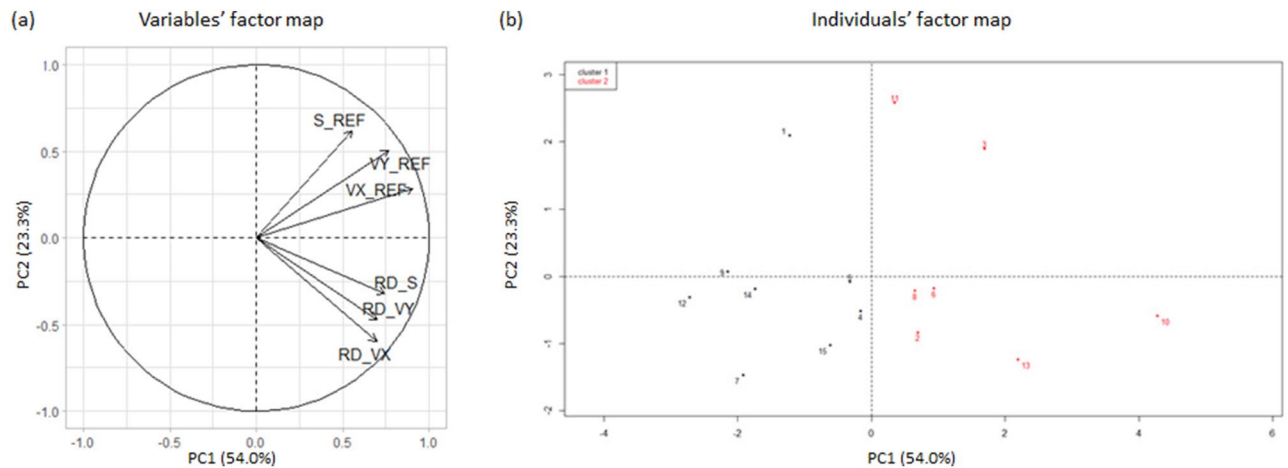


Figure 2. Variables' (a) and individuals' (b) factor map of the PCA applied on COP parameters in the UNSTA postural task. Individuals from cluster 1 and 2 are represented by black and red dots respectively. *S_REF* COP surface area in the REF condition, *VX_REF* mean COP velocity along the medio-lateral axis in the REF condition, *VY_REF* mean COP velocity along the antero-posterior axis in the REF condition, *RD_S*, *RD_VX* and *RD_VY* relative difference between both conditions ($RD = 100 \cdot [CG - REF] / REF$) of *S*, *VX* and *VY* variables.

high inter-individual variability in the ability to benefit from CG wearing to improve balance control is present within a group of high-level athletes.

CG act by applying frictional forces to the skin, which direction and size are related to the body sway movements¹³. As initially observed in studies about the effects of passive tactile cues on balance control²⁹, these forces activate both slow and fast-adapting cutaneous mechanoreceptors to provide additional sensory cues that are integrated by the central nervous system to reduce body sway when a sensory pathway critical for standing posture has been perturbed (e.g. when vision is occluded). The stimulation of cutaneous inputs from the lower leg induced by the wearing of CG can also depress the H-reflex by activating Ia inhibitory interneurons¹⁶. Because an early spinal reflex can provoke small reactive and uncontrolled movements that can be a source of postural instability³⁰, there is a relationship between the amplitude of the H-reflex and that of the displacement of the COP: the lower the amplitude of the H-reflex, the lower the postural sway^{30,31}. Even though the differences in COP parameters were not statistically significant among experimental conditions, the tendencies to an improved balance control with CG ($P = 0.073$ and $P = 0.083$ for *VX* and *VY* respectively) could reflect an efficient sensory reweighting mechanism³² with an up-weighting of the additional cutaneous information provided by CG to compensate for the lack of visual cues in the STA postural task. Indeed, garments that stimulate lower limbs cutaneous receptors (e.g. CG, braces and tapes) rather positively influence balance control when somatosensory information is altered by experimental manipulations^{13,33,34}. These garments had more limited effects when standing on unstable supports (e.g. wobble board as in the present study) or performing dynamic tasks (e.g. Y balance test)^{17,20}, likely due to the availability of visual cues and the increased contribution of vestibular and proprioceptive cues due to greater joint movements³⁵ which might have limited an up-weighting of the additional somatosensory cues provided by CG.

Results from the PCA showed that there was a high variability between individuals' responses to CG wearing within a population of professional elite athletes. This heterogeneity among the ability of participants to benefit from CG wearing to improve balance control could explain the controversial results about the influence of compression garments on balance control in healthy young subjects^{13,14,17,18,20,24}. In both STA and UNSTA postural tasks, the HCA also provided evidence that this variability did not present a random structure, but was structured in two clusters of participants with similar characteristics. Subjects from cluster 1, while presenting lower values of postural variables in the REF condition, exhibited a more efficient balance control at baseline than subjects from cluster 2. Interestingly, only subjects from cluster 1 benefited from CG wearing to improve their balance control, while presenting negative values of RD of COP parameters between CG and REF condition. Individuals from cluster 2 presented positive value of RD and did not benefit from CG wearing. This link between balance control efficiency at baseline and the ability to take advantage of CG to improve balance control can potentially stem from (1) differences in participant's preferred sensorimotor tactics and/or (2) differences in participants' intrinsic balance/proprioceptive abilities.

Individuals vary in the degree to which they weight sensory inputs to control their balance³². Earlier reports about sensory reweighting in balance control during sensory perturbations have provided evidence that subjects from a homogeneous sample could respond differently to sensory perturbations depending on preferred modes of spatial referencing^{36–38}. Two main *preferred sensorimotor tactics* have been identified. Some subjects, called *support-dependent*, rely more on the exploitation of the geometry of the support surface as a reference frame by assigning a high weight to somatosensory cues from ankle-foot proprioceptive and plantar cutaneous mechanoreceptors. Other subjects, called *gravity-dependent*, rely more on gravito-inertial signals by assigning a high weight to kinetic-graviceptive vestibular cues and/or to proprioceptive cues stemming from joints and muscles with a higher position in the kinematic chain (i.e. hip, trunk and neck joint muscles)^{36–38}. Isableu & Vuilleme showed that subjects who had to sway as little as possible on stable ground with the eyes closed differently

regulated their balance according to their preferred sensorimotor tactics³⁶. Support-dependent subjects swayed less than gravity-dependant subjects, by minimising angular variations of the ankle with respect to the support. On the other hand, gravity-dependent subjects exhibited larger postural sway while adopting a more exploratory behaviour in order to extract kinetic-graviceptive information more efficiently³⁶. In the present study, individuals from cluster 1, who swayed less than those from cluster 2, had a typical profile of support-dependent subjects, while individuals from cluster 2 may be characterized as gravity-dependent subjects. Isableu & Vuillerme also showed that support-dependent subjects were more sensitive to somatosensory alteration of the feet-support than gravity-dependent ones³⁶. In the same manner, individuals from cluster 1 exhibited a greater sensitivity to somatosensory manipulation by being the only participants to take advantage of CG to improve balance control, thus supporting the idea that they would present a support-dependent preferred sensorimotor tactic.

Even though athletes exhibit better balance control than non-athletes^{25,39}, such a heterogeneity of balance regulation mechanisms within our group of athletes might also stem from individual natural predispositions that would persist despite years of training⁴⁰. It is known that the contribution of proprioception in balance regulation is increased in athletes and that elite athletes have superior proprioceptive abilities than sub-elite or non-athletes^{25,41}. Nevertheless, Han et al. showed that superior proprioceptive abilities in high-level athletes was not correlated with training experience but was rather constrained by genetically determined factors⁴¹. Hence, it can be hypothesised that athletes from cluster 1 had exceptional neurobiologically determined proprioceptive acuity that enabled them to benefit from CG wearing through optimal sensory reweighting. The ability to take advantage of garments that stimulate cutaneous receptors such as CG to improve balance control seems to describe a U-shaped relationship according to subjects' balance and/or proprioceptive abilities. Beneficial effects are reported in individuals with poor proprioceptive acuity and/or balance^{24,42} and with individuals with good proprioceptive acuity and/or balance¹³, whereas no beneficial effects are reported in healthy non-athletes subjects with "ordinary" balance and/or proprioceptive acuity^{17,18,20,24}.

A limitation of the study is that although CG were individually fitted by choosing proper sizing according to the individual calf size and height, we did not measure the interface pressure applied by the CG. According to the manufacturer's information, the CG used in this study are expected to provide a 19 mmHg pressure level over the calf. Due to the sizing issue, however, it is possible that 19 mmHg is not always the pressure actually applied. For example, with a M size suitable for a 38–43 cm calf circumference range, the pressure exerted by the CG should be higher with a circumference of 43 cm compared to 38 cm. In this case, the more intense pressure on the skin may provide a greater cutaneous stimulus with a larger impact on balance control. The fact that a commercially manufactured CG does not provide a homogeneous compression level with the same size might modulate the effects of CG on balance control. Hence, in the present study, this could also have influenced the distribution of the individuals within the different clusters. Nevertheless, studies that have tested the effects of wearing CG of different compression levels reported that the level of compression had no influence on balance control^{15,19–22}, thus suggesting that the level of compression is not the most crucial factor that modulates the effects of CG on balance control. However, future studies should be conducted to specifically examine the influence of compression heterogeneity actually provided by a CG model of a given size on balance control. Further experiments are also needed to assess athletes' preferred sensorimotor tactics (through sensory perturbation paradigms) and intrinsic proprioceptive abilities in order to explore the influence of these two factors on the ability of athletes to take advantage of CG to improve balance control.

Conclusions

This study showed that among a sample of professional handball players with more than 15 years' experience, only athletes with the best balance abilities at baseline could benefit from CG wearing to improve their balance control. Hence, it can be suggested that the ability to benefit from CG wearing to improve balance control depends on elite athletes' intrinsic balance abilities and/or preferred sensorimotor tactics. The present finding emphasizes the necessity to address the issue of inter-individual variability when studying the effects of CG on balance control.

Methods

Participants. Fifteen male handball players from the same team in the professional French National Handball League (age: 25.06 ± 4.19 years old, height: 190.5 ± 5.73 cm; body mass: 94.2 ± 12.25 kg; years of practice: 15.94 ± 5.15 years; mean ± SD) were recruited. All participants had equal training volume (13 h of training including one 60-min handball game per week). Exclusion criteria included any neuromuscular impairments and/or ankle, knee, hip trauma in the past 2 years and medication that might influence balance. Participants were also asked to avoid strenuous activity and the ingestion of alcohol or/and exciting substances 24 h before the experimental session. All participants voluntarily signed an informed consent form before starting the experiment, which was in accordance with the Helsinki Declaration. All procedures were approved by and performed in accordance with the relevant guidelines and regulations of the University of Pau and Adour Countries Ethics Committee.

Balance control assessment. Participants were asked to stand barefoot and to sway as little as possible in a monopodal stance on their non-dominant leg for 25 s on a force platform (STABILOTEST TECHNO CONCEPT, Mane, France) which sampled the centre of foot pressure (COP) displacements at 40 Hz. The non-dominant leg (i.e. the supporting leg, which was determined as the leg which is not used to kick a ball) was chosen because handball is an asymmetric activity which requires frequent phases of monopodal stance on the non-dominant leg (e.g. while passing, jumping and shooting). A wobble board with a diameter of 40 cm and a height of 8 cm (Balance-board, SISSEL GmbH, Bad Dürkheim, Germany) could be placed on the force platform to generate instability. For accurate and similar feet positioning between all subjects, the foot was placed

according to precise landmarks on the force platform and the wobble board. Subjects had the supporting leg extended and the other leg flexed with the big toe positioned at the level of the malleolus of the other leg (without any contact). They were also asked to cross the arms in front of the chest while touching the border of the clavicle with the forefinger. Two postural tasks were considered: a stable task (STA) where participants stood on stable ground with the eyes closed (while keeping their gaze in a straight-ahead direction) and an unstable task (UNSTA) where they stood on the wobble board with the eyes open (while looking at a fixed level target at a distance of 2 m). All postural tasks were performed with or without wearing compression garments (i.e., in the CG condition and the REF condition respectively). Two familiarization trials were performed for each postural task before data acquisition in order to avoid any learning effect⁴³. COP surface area (S: 90% confidence ellipse), mean COP velocity along the medio-lateral (VX) and antero-posterior (VY) axes were calculated to characterize balance control; the lower these parameters, the more efficient the balance control⁴⁴. In the CG condition, progressive calf compression sleeves composed of 69% Polyamide, 21% Elastane and 10% Yarn (BOOSTER Elite, BV SPORT, Saint Etienne, France) were worn by the participants. These CG provide a pressure that increases gradually from 13 mmHg at the ankle to 19 mmHg at the gastrocnemius. CG size was individualized according to guidelines of the manufacturers, based on participants' height and calf circumference. Four sizes were used: M+, L+, XL+ and XXL+, sized for 34–38 / > 175, 38–43 / > 175, 38–43 / > 192, 43–48/192 (calf circumference/height, in cm) respectively so as to accommodate all participants' body shape.

Statistical analysis. The two postural tasks (STA and UNSTA) were analyzed independently. The first step of the analysis consisted of evaluating the influence of CG with a standard whole group analysis. Since the data did not meet the assumption of normal distribution (tested with the Shapiro–Wilk test), non-parametric Wilcoxon signed rank tests were applied to compare each dependent variables (S, VX, VY) between the REF and CG conditions. A standardized principal component analysis (PCA) was also applied as a multivariate approach in order to conduct a more subtle descriptive analysis of variability between subjects, while identifying potential linear links between variables. COP parameters in the REF condition and the relative differences (RD) of each COP parameter between both conditions ($RD = 100 * [CG - REF] / REF$) were used as input values in the PCA. RD is an easily interpretable descriptor, which limits the influence of the heterogeneity between participants in the REF condition and makes it easy to differentiate participants who benefit from CG wearing (negative value of RD) and those who do not (positive value of RD). Finally, a hierarchical cluster analysis (HCA)⁴⁵ was used in a stepwise fashion on the basis of the principal component scores obtained from the PCA, to categorize the participants' behaviours into subgroups with similar characteristics (i.e. with low or high COP values in the REF condition and low or high RD values)^{27,28}. Statistical analyses were performed with R statistical software. The significance level was set at $P < 0.05$ and tendencies were reported when $0.05 \leq P < 0.1$.

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Author contributions

K.B., F.N. and T.P. conceived and designed research. K.B. conducted experiments. K.B., F.N. and T.P. analyzed data. K.B., F.N. and T.P. wrote the manuscript. All authors read and approved the manuscript.

Competing interests

The authors declare no competing interests.

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Can Compression Garments Reduce Inter-Limb Balance Asymmetries?

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Sensory cues provided by compression garments (CG) can improve movement accuracy and potentially reduce inter-limb balance asymmetries and the associated risk of injury. The aim of this study was to analyze the effects of CG wearing on inter-limb balance asymmetries. The hypothesis was that CG would reduce inter-limb balance asymmetries, especially in subjects with high level of asymmetries. Twenty-five sportsmen were recruited. They had to stand as motionless as possible in a one-leg stance in two postural tasks (stable and unstable), while wearing CG or not. Asymmetry indexes were calculated from center of foot pressure parameters. The effects of CG wearing were analyzed according to participants' baseline level of asymmetry (i.e., without wearing CG) with correlation analyses. A qualitative analysis was also performed after a dichotomization procedure to check for a specific influence of CG on the dominant and non-dominant leg. Inter-limb balance asymmetries were reduced with CG in participants with high levels of asymmetries at baseline. However, asymmetries were increased with CG in participants with low levels of asymmetries at baseline. The dominant leg was more affected by this negative effect. CG wearing could reduce inter-limb balance asymmetries and the related injury risk in subjects with high levels of inter-limb balance asymmetries at baseline. Nevertheless, CG should not be used in individuals with low baseline balance asymmetries since it can increase asymmetries in these subjects, likely by confusing and overloading the sensorimotor processing on the dominant leg.

Keywords: laterality, symmetry, posture, balance control, compression garments

INTRODUCTION

Asymmetries between two limbs are prevalent in human movement. They are characterized by a difference in performance between the right and left limbs and/or the preferential use of one side of the body (i.e., left or right) to perform a motor action (Schneiders et al., 2010; Bishop et al., 2018). The etiologies of inter-limb asymmetries are related to lateralization in sensorimotor control originating from cerebral hemispheric asymmetry (Promsri et al., 2018, 2019; Marcori et al., 2020; Liu et al., 2021) and biomechanical factors (e.g., bilateral asymmetry in the bones length, imbalance of muscle strength between the left and right limb) (Auerbach and Ruff, 2006; Bishop et al., 2018). Inter-limb asymmetries can be modulated by numerous factors. Injuries and pathologies such as anterior cruciate ligament injuries (Mohammadi et al., 2012) or scoliosis (Yang et al., 2013) increase inter-limb asymmetries. Subjects affected by neurologic conditions (e.g., stroke

and multiple sclerosis) and individuals with experience in asymmetric sports (e.g., soccer, volley-ball, and hand-ball) also demonstrate pronounced inter-limb asymmetries (Chisholm et al., 2011; Paillard and Noé, 2020; Pau et al., 2021).

Inter-limb asymmetries can have a negative impact on sports performance and are associated with a high incidence of lower-limb injury, especially if asymmetries concern balance control (Stiffler et al., 2017; Bishop et al., 2018; Promsri et al., 2019). Actually, inter-limb balance asymmetries may impair the ability to shift the body weight onto one leg thus negatively impacting sports-related actions such as sidestepping or changes of direction and predisposing sportspeople to non-contact lower-limb injury (Bishop et al., 2018; Dos'Santos et al., 2019; Promsri et al., 2019). Therefore, training strategies such as balance training, resistance training or warm-up programs, can be implemented to minimize inter-limb balance asymmetries, improve balance control and reduce the relative risk of sports-related non-contact injury (Bishop et al., 2018; Pardos-Mainer et al., 2019; Madruga-Parera et al., 2020). Affordable external devices that interact with cutaneous receptors such as compression garments (CG) can also acutely improve balance control (Kuster et al., 1999; Michael et al., 2014; Woo et al., 2017; Baige et al., 2020). The constriction provided by CG acts as a mechanically supportive framework that can activate interacting cutaneous mechanoreceptors that individually would not have been activated (Baige et al., 2020), thus improving movement accuracy during tasks that include a large somatosensory component (Hasan et al., 2016; Ghai et al., 2018; Broatch et al., 2021) and offering a potential benefit in reducing inter-limb balance asymmetries. Nevertheless, to our knowledge, no study has specifically investigated the effects of CG wearing on inter-limb balance asymmetries.

Hence, this study was undertaken to investigate the effects of CG on inter-limb balance asymmetries in individuals with extensive experience in an asymmetric sport such as handball players. Handball is a sport involving asymmetric motor actions (lower and upper limbs) that can accentuate inter-limb asymmetries, which might negatively affect athletic performance and increase the risk of lower extremity injuries (Steib et al., 2016; Paillard, 2017; Barrera-Domínguez et al., 2021). Thus, a passive intervention such as CG wearing is hypothesized to reduce inter-limb balance asymmetries, especially in subjects with a high level of asymmetry, and could represent a cost effective sport-related injury prevention strategy.

MATERIALS AND METHODS

Participants

Twenty-five young handball players (age: 27.1 ± 6.9 years old, height: 184.8 ± 8.1 cm; body mass: 87.2 ± 15.3 kg; mean \pm SD) who reported no neuromuscular problems in the past 2 years volunteered for the current study. Participants were recruited from two regional semi-professional teams. They were asked to avoid strenuous activity and the ingestion of alcohol or/and excitatory substances 24 h before the experimental session. A written informed consent was obtained from all participants

before starting the experiment, which was in accordance with the Declaration of Helsinki. All procedures were approved by and performed in accordance with the relevant guidelines and regulations of the University of Pau and Pays de l'Adour Ethics Committee.

Apparatus and Procedure

Participants were asked to sway and move as little as possible when standing barefoot in a one-leg stance for 25 s on a force platform (Stabilotest® Techno Concept™, Mane, France) which sampled the displacements of the center of foot pressure (position of the point of application of the vertical ground reaction force) at 40 Hz. Two postural tasks were conducted: a stable task where participants stood directly on the force platform (on stable ground) with their eyes closed (while keeping their gaze straight ahead) and an unstable task where they stood with their eyes open (while looking at a fixed level target at a distance of 2 m) on a wobble board with a diameter of 40 cm and a height of 8 cm (Balance-board, Sissel® GmbH, Bad Dürkheim, Germany) which was placed on the force platform to generate instability. For accurate and similar feet positioning between all participants, the platform and the wobble board were marked with a central horizontal line, and participants were required to align the middle of the foot with the mark (the middle of each foot was delimited beforehand). The center of the wobble board was also aligned with the center of the force platform.

Postural tasks were performed with or without wearing compression garments (CG and REF condition, respectively). In the CG condition, calf compression sleeves (Booster, BV sport®, Saint Etienne, France) made of 79% Polyamide and 21% Elastane, were worn by the participants (Figure 1). According to the manufacturer's specifications, these garments provide a pressure that increases gradually from 13 mmHg at the lower part of the calf to 20–25 mmHg at the gastrocnemius belly (20 mmHg at the lateral part and 25 mmHg at the medial part). The size of the compression sleeves was individually fitted according to guidelines of the manufacturers, based on participants' height and calf circumference. Four sizes were used: M+, L+, XL+, and XXL+, sized for 34–38/>175, 38–43/>175, 38–43/>192, 43–48/192 (calf circumference/height, in cm), respectively, so as to accommodate all participants' body shape. Participants performed a set of three trials in each postural task (stable and unstable) and condition (REF and CG) with each set completed in a randomized order to avoid any learning effect. The first two trials were not recorded and served as familiarization trials. Since a stable and reliable balance score is achieved at the third trial in a one one-leg stance (Cug and Wikstrom, 2014), only the third trial was recorded and considered for statistical analysis for each postural task and in each experimental condition. Subjects were sitting quietly on a chair for 2 min between balance assessments.

Analysis of Data

The following parameters of the center of pressure were initially calculated: mean velocity (sum of the cumulated COP displacement divided by the trial time) along the medio-lateral (VX) and antero-posterior (VY) axes and surface area (S: 90% confidence ellipse) (Paillard and Noé, 2015). Based on the method



FIGURE 1 | Compression sleeves worn by participants in the compression garments (CG) condition.

proposed by Read et al. (2018) and Fort-Vanmeerhaeghe et al. (2020), an asymmetry index (ASY) between both legs was then calculated for each center of pressure parameter (ASY_VX, ASY_VY, ASY_S) as follows:

$$\text{ASY} (\%) = \text{ABS} \left(\frac{(\text{Highest performing limb} - \text{Lowest performing limb})}{\text{Highest performing limb}} \right) \times 100,$$

with ABS: absolute value.

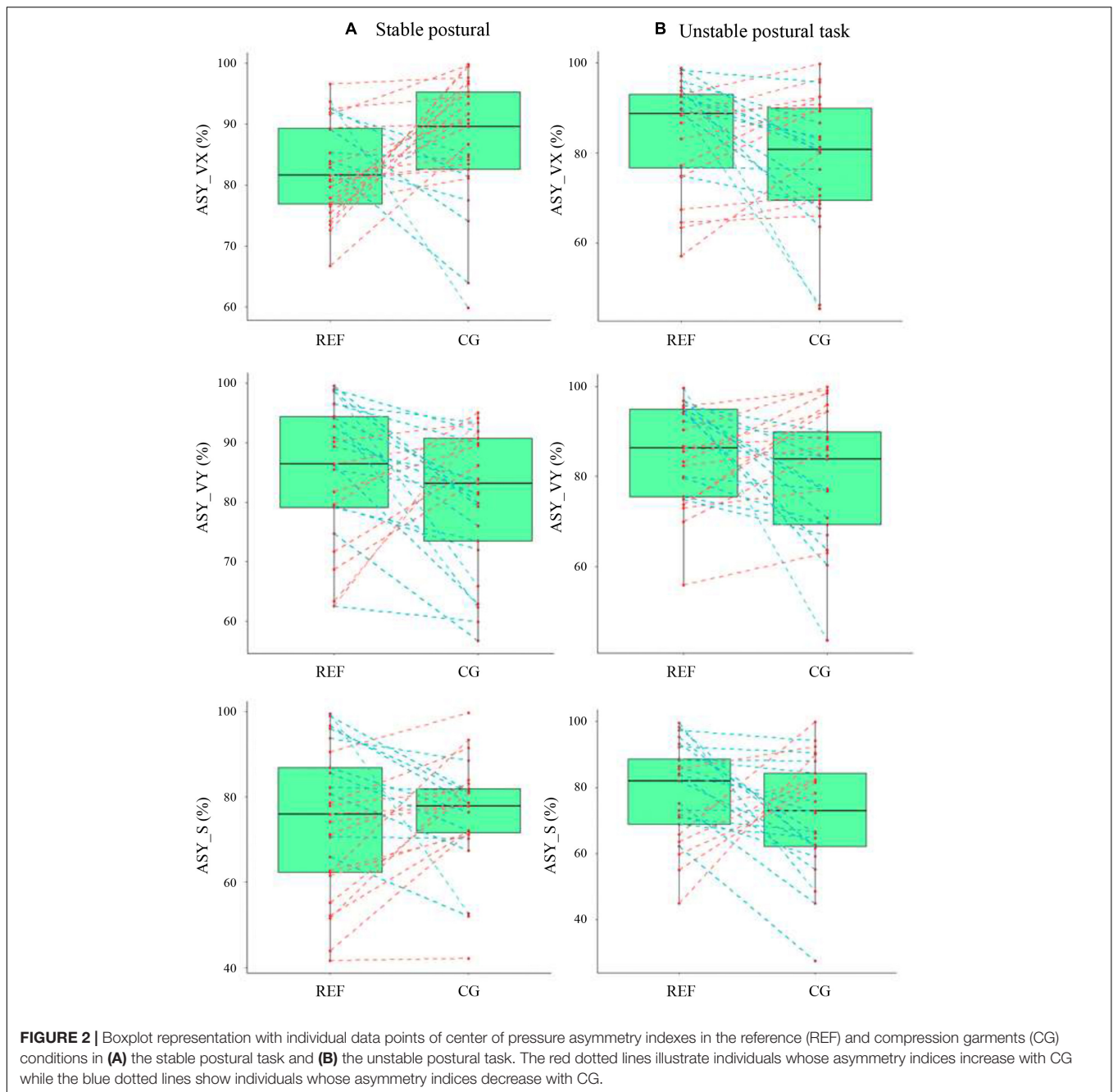
When considering that with participants who were asked to sway as little as possible when standing upright, the lower the center of pressure parameters (i.e., VX, VY, S), the more efficient the balance control (Paillard and Noé, 2015), the highest performing limb was then defined as the side with the lowest center of pressure value.

Statistical Analysis

The two postural tasks (stable and unstable) were analyzed independently. Normality was tested using the Shapiro–Wilk test. As the dependent variables (ASY_VX, ASY_VY, and ASY_S)

did not meet the assumption of normal distribution, non-parametric Wilcoxon sign rank tests were applied to determine differences between the CG and REF conditions. The difference of each asymmetry index between the CG and REF conditions (difference = CG - REF) was also calculated to easily differentiate participants who benefit from CG wearing to reduce inter-limb balance asymmetries (negative difference) and those who do not (positive difference). Then, Spearman's rank order correlations were undertaken between asymmetry indexes at baseline (i.e., in the REF condition) and differences in asymmetry between the REF and CG conditions to assess whether the beneficial effects of CG in reducing inter-limb balance asymmetries was related to the participant's inter-limb balance asymmetries at baseline.

A qualitative analysis was also carried out to check for a specific influence of compression garments on balance control of the dominant and non-dominant leg, determined by the preferred kicking leg (Paillard and Noé, 2020). A dichotomization method was performed on the center of pressure parameters to characterize three levels of CG influence on balance control: a negative influence, a negligible influence and a positive influence. The following are the thresholds used in the dichotomization procedure: a negative influence was considered when the value in the CG condition exceeded that in the REF condition by more than 10%; a negligible influence was considered when the difference between either conditions did not exceed 10%; a positive influence was considered when the value in the REF condition exceeded that in the CG condition by more than 10%. χ^2 -conformity tests were independently performed on DL and NDL data to test the null hypothesis (similar distribution of individuals for whom CG have a negative, negligible, or positive influence on balance control). This qualitative analysis was performed on the whole sample and on subgroups of individuals in order to check whether individuals who benefited from CG to decrease inter-limb balance asymmetries and those who do not were differently affected by the wearing of CG on the dominant and non-dominant leg. Sub-groups were formed by distinguishing subjects in whom CG wearing had no substantial influence on asymmetry indexes ("unchanged asymmetry with CG" subgroup, i.e., with an increase/decrease of the asymmetry index between REF and CG conditions of less than 10%), subjects in whom CG wearing markedly increased the level of asymmetry ("increase in asymmetry with CG" subgroup, i.e., with an increase of the asymmetry index of more than 10% in the CG condition) and subjects in whom CG wearing markedly decreased the level of asymmetry ("decrease in asymmetry with CG" subgroup, i.e., with a decrease of the asymmetry index of more than 10% in the CG condition). Based on previous studies about reliability of center of pressure-based postural sway measures during one-leg stance in young healthy participants, the 10% threshold was chosen to distinguish between clear and unclear changes due to measurement noise (Lin et al., 2008; Muehlbauer et al., 2011; da Silva et al., 2013). The relationships between subgroups of individuals and specific influence of CG on the dominant and non-dominant leg were then tested with the Fisher's exact test after having constructed contingency tables. Statistical analyses were performed with R statistical software. The significance level was set at $p < 0.05$.

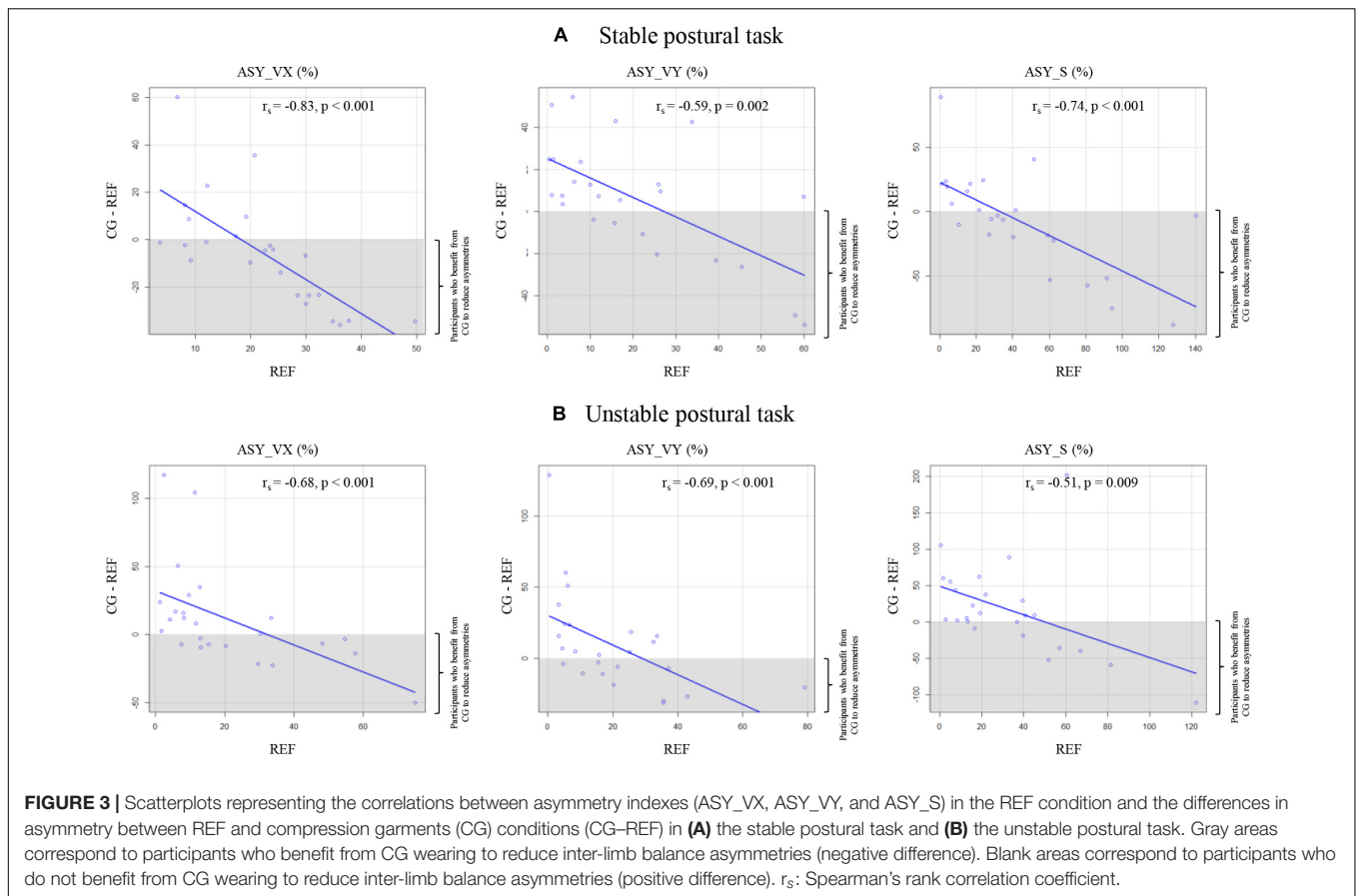


RESULTS

Figure 2 illustrates boxplots with individual data points of asymmetry indexes in the REF and CG conditions. No significant differences were observed between REF and CG conditions in both the stable and unstable postural tasks. When focusing on the individual data points, one could notice that the asymmetry indexes did not evolve similarly among participants between the REF and CG conditions: asymmetry indexes increased with CG in some participants (red dotted lines on **Figure 2**), while asymmetry

indexes decreased with CG in others (blue dotted lines on **Figure 2**).

Scatterplots illustrating correlations between ASY indexes in the REF condition and the differences between the CG and REF conditions are shown in **Figure 3**. In both stable and unstable postural tasks and for all asymmetry indexes, there were significant and large relationships between asymmetry indexes in the REF condition and asymmetry differences between CG and REF conditions. This result indicates that high levels of inter-limb balance asymmetry at baseline [approximate (40–120%) range of asymmetry] was associated with negative differences between



CG and REF conditions (i.e., a beneficial effect of CG wearing in reducing inter-limb balance asymmetries). On the contrary, low levels of inter-limb balance asymmetry at baseline [approximate (0–40%) range of asymmetry] were rather associated with positive differences between CG and REF conditions (i.e., an increase of inter-limb balance asymmetries when wearing CG).

Table 1 shows the distribution of participants according to the influence of CG wearing (negative, negligible, or positive influence) on balance control of the dominant and non-dominant leg in the whole sample and in subgroups of individuals. In the stable postural task, results from χ^2 conformity tests performed in the whole sample were not significant, thus illustrating a homogeneous distribution among participants with a negative, negligible or positive influence of CG wearing on balance control of the dominant or the non-dominant leg. In this postural task, results from the Fisher's exact test were also not significant. In the unstable postural task, results from the χ^2 conformity test applied on participants' distribution based on S data on the dominant-leg showed a significant difference from an equal distribution ($\chi^2 = 6.08; p < 0.05$), with an under-representation of individuals for whom CG wearing had negligible influence on the dominant-leg. When the χ^2 test was applied on participants' distribution based on VY data on the non-dominant leg, a significant difference from an equal distribution ($\chi^2 = 11.12; p < 0.004$), with an over-representation of individuals for whom CG wearing had negligible influence on balance control of the

non-dominant leg. Results from the Fisher's exact test showed a significant association between subgroups of participants and CG influence on balance control on the dominant leg when participants' distribution were based on VX ($p < 0.003$) and VY data ($p < 0.005$). Individuals in whom CG wearing markedly increased the level of asymmetry were negatively influenced by CG wearing on the dominant leg. Results from the Fisher's exact test did not show any significant association between subgroups of participants and CG influence on balance control of the non-dominant leg.

DISCUSSION

The aim of this study was to analyze the effects of CG wearing on inter-limb balance asymmetries. The hypothesis was that CG would reduce inter-limb balance asymmetries, especially in subjects with high level of asymmetries. When using a standard statistical approach with pairwise comparisons between group levels, our results showed that the wearing of CG was not associated with a significant reduction of inter-limb balance asymmetries. However, when analyzing the effect of CG wearing according to participants' initial level of asymmetry, results from correlation analyses indicated that beneficial effects of CG in reducing inter-limb balance asymmetries were related to participant's asymmetry levels at baseline. Only participants

TABLE 1 | Distribution of participants according to the influence of compression garments (CG) wearing (negative, negligible, or positive) on the dominant and non-dominant leg in the whole sample and in subgroups of individuals.

			Stable task			Unstable task			
			Negative	Negligible	Positive	Negative	Negligible	Positive	
VX	Whole sample	Dominant leg	9	10	6	10	9	6	
		Non-dominant leg	5	12	8	8	11	6	
	Subgroups	Decrease in asymmetry with CG	Dominant leg	5	2	3	4	0	3
		Non-dominant leg	2	4	4	1	3	3	
	Unchanged asymmetry with CG	Dominant leg	1	6	2	0	6	0	
		Non-dominant leg	1	6	2	1	5	0	
Increase in asymmetry with CG	Dominant leg	3	2	1	6	3	3		
	Non-dominant leg	2	2	2	6	3	3		
VY	Whole sample	Dominant leg	10	8	7	10	7	8	
		Non-dominant leg	6	10	9	3	16	6	
	Subgroups	Decrease in asymmetry with CG	Dominant leg	3	2	3	3	3	3
		Non-dominant leg	1	4	3	2	5	2	
	Unchanged asymmetry with CG	Dominant leg	1	1	0	0	4	0	
		Non-dominant leg	1	1	0	0	4	0	
Increase in asymmetry with CG	Dominant leg	6	5	4	7	0	5		
	Non-dominant leg	4	5	6	1	7	4		
S	Whole sample	Dominant leg	11	3	11	13	3	9	
		Non-dominant leg	9	7	9	8	8	9	
	Subgroups	Decrease in asymmetry with CG	Dominant leg	3	2	7	4	0	3
		Non-dominant leg	6	3	3	2	3	2	
	Unchanged asymmetry with CG	Dominant leg	1	1	2	1	2	1	
		Non-dominant leg	0	1	3	0	3	1	
Increase in asymmetry with CG	Dominant leg	7	0	2	8	1	5		
	Non-dominant leg	3	3	3	6	2	6		

Subgroups of individuals were formed by distinguishing subjects in whom CG wearing had no substantial influence on asymmetry indexes ("unchanged asymmetry with CG" subgroup), subjects in whom CG wearing markedly increased the level of asymmetry ("increase in asymmetry with CG" subgroup) and subjects in whom CG wearing markedly decreased the level of asymmetry ("decrease in asymmetry with CG" subgroup).

VX, mean velocity of the center of pressure along the medio-lateral axis; VY, mean velocity of the center of pressure along the antero-posterior axis; S, center of pressure surface area (90% confidence ellipse).

with high levels of inter-limb balance asymmetries at baseline benefited from CG to decrease inter-limb balance asymmetries.

Inter-limb balance asymmetries are mainly related to differences in somatosensory processing between both legs originating from cerebral hemispheric asymmetry (Promsri et al., 2018, 2019; Marcori et al., 2020; Liu et al., 2021). Within the perspective of the dynamic dominance model of laterality (Sainburg, 2005, 2014), one hemisphere (the left hemisphere for right-handed individuals) would rather be specialized in limb trajectory control, whereas the other hemisphere would rather be specialized for impedance control—i.e., control of limb position and maintenance of a stable posture (Sainburg, 2005, 2014; Marcori et al., 2020). Lateralization of impedance control is based on hemisphere specialization for the utilization of somatosensory cues (Goble et al., 2006; Sainburg, 2014; Liu et al., 2021), which is characterized by the superiority of one hemisphere in processing somatosensory information (the right hemisphere for right-handed individuals), thus resulting in better proprioception of one limb (the left limb for right-handed individuals) compared to the other (Carnahan and Elliott, 1987; Goble et al., 2006). Participants' injury history and/or experience

in asymmetric motor practices can modulate lateralization of impedance control and increase the difference in somatosensory processing between the two legs, thus inducing large inter-individual differences of balance inter-limb asymmetry (Marcori et al., 2019; Paillard and Noé, 2020).

When wearing CG, frictional forces that activate both slow and fast-adapting cutaneous mechanoreceptors are applied to the skin, which can improve joint position sense and balance control (Kuster et al., 1999; You et al., 2004; Cameron et al., 2008; Michael et al., 2014; Woo et al., 2017; Baige et al., 2020; Broatch et al., 2021). In the present study, there was a great heterogeneity in the ability of participants to benefit from CG wearing to reduce inter-limb balance asymmetries. Previous studies about the effects of CG on functional somatosensory abilities have produced concordant findings while reporting a strong inter-individual variability in responses to the wearing of CG in young healthy participants (You et al., 2004; Cameron et al., 2008; Broatch et al., 2021). After ranking participants according to their score in a movement discrimination task, these studies showed that only participants with poor lower limb somatosensation benefited from the wearing of CG to improve joint position

sense, thus illustrating that the magnitude of the beneficial effects of CG wearing was inversely related to the participant's somatosensation at baseline. Similar findings were observed with other stimulation strategies such as ankle taping (Long et al., 2017), textured insoles (Steinberg et al., 2016), and vibration stimulation (Liu et al., 2021).

In the present study, participants with high levels of inter-limb balance asymmetries at baseline benefited from CG wearing to reduce inter-limb balance asymmetries. However, in both the stable and unstable postural tasks, the data from the qualitative analysis about the specific influence of CG on both legs (**Table 1**) did not illustrate a stronger influence of CG on the dominant leg or the non-dominant leg in individuals who benefited from CG wearing to markedly decrease inter-limb asymmetries. In participants with low levels of inter-limb balance asymmetries at baseline, CG were unhelpful and could also increase inter-limb-balance asymmetries in some participants. Further studies reported analogous findings while showing that proprioceptive acuity decreased in participants with higher levels of proprioceptive ability when they wore external devices that stimulate cutaneous receptors (Cameron et al., 2008; Steinberg et al., 2016; Long et al., 2017; Liu et al., 2021). These authors postulated that in subjects with a high proprioceptive acuity at baseline, the application of an external stimulation device confused and overloaded the sensorimotor system by delivering redundant information, thus resulting in an impaired proprioceptive ability. Liu et al. (2021) noticed that proprioception deteriorated only in the dominant leg in individuals with high proprioceptive acuity following stimulation of the calf muscles with a vibrating foam roller. Our results from the qualitative analysis also suggest that, in the most challenging postural task (i.e., the unstable postural task) CG wearing would have a greater impact on the dominant leg and, more specifically, that CG negatively influenced balance control only on the dominant leg in participants in whom CG wearing increased inter-limb asymmetries. Our results therefore seem to confirm the hypothesis formulated by Liu et al. (2021) about different effects of the application of external stimuli on different hemispheres and show that the non-dominant hemisphere would be less sensitive to somatosensory stimulation.

A limitation of the current research is the absence of measure of the pressure exerted by the calf compression sleeves. Although compression sleeves were individually fitted by following the manufacturer's specifications and choosing proper sizing according to individuals' calf circumference, commercially manufactured compression garments do not provide exactly the same level of compression in all subjects. Potential differences in the pressures exerted by the CG might modulate the effects of CG on inter-limb balance asymmetries. Nevertheless, studies

that have tested the effects of CG providing various compression levels on balance control did not report any significant differences attributed to the level of compression (e.g., Hijmans et al., 2009; Jaakkola et al., 2017; Woo et al., 2018). It should be noted that the compression sleeves used in this study did not cover the ankle joint, whereas somatosensory information from the ankle joint plays an essential role in balance control (Han et al., 2015). Hence, one can hypothesize that the use of CG covering the ankle joints such as compression socks could potentially provide larger benefits in reducing inter-limb balance asymmetries. Further experiments are needed to explore the influence of various designs of CG (e.g., full leg CG, compression socks, calf and knee compression sleeves) on inter-limb balance asymmetries.

The present study provides new insights about the influence of CG on inter-limb balance asymmetries. From a practical point of view, these results suggest that CG wearing could reduce inter-limb balance asymmetries and the related injury risk in participants with high levels of inter-limb balance asymmetries at baseline. In return, since it rather increases asymmetries in participants having low baseline balance asymmetries, CG wearing should be avoided in these participants.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by the University of Pau and Adour Countries Ethics Committee. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

FN, KB, and TP designed the study. KB acquired the data. FN analyzed the data and wrote the manuscript, while KB and TP revised it. All authors signed the final approval for publication.

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Résumé

L'objectif général de ce travail de thèse était d'analyser les effets du port de vêtements de compression sur le contrôle postural. Les vêtements de compression stimulent les récepteurs cutanés au niveau des zones compressées. Même si cette stimulation tactile est susceptible d'améliorer le contrôle postural, la littérature fait état d'une grande hétérogénéité dans les réponses à ce type de stimulation en fonction de la typologie des participants recrutés. Aussi, la question des effets de la stimulation tactile fournis par les vêtements de compression sur le contrôle postural reste ouverte, notamment chez les sujets jeunes où l'expérience sportive semble moduler les réponses. Nous avons donc analysé les effets des vêtements de compression sur le contrôle postural de sujets jeunes actifs et de sportifs de haut niveau. Nos résultats ont montré qu'il existait une forte variabilité des réponses inter-individuelles au sein de ces deux échantillon de participants. Des analyses statistiques de classification hiérarchique en cluster ont permis d'identifier des sous-groupes d'individus qui réagissaient différemment à la compression chez ces deux types de sujets. La faculté des participants à tirer profit du port des vêtements de compression semble être liée à leurs capacités initiales d'équilibration et/ou à leurs stratégies sensorimotrices préférentielles.

Mots clés : contrôle postural, vêtements de compression, posture, variabilité inter-individuelle, stratégie sensorimotrice

Abstract

The general aim of this thesis was to analyse the effects of wearing compression garments on postural control. Compression garments stimulate skin receptors in the compressed areas. Although this tactile stimulation is likely to improve postural control, the literature reports a great heterogeneity in the response to this type of stimulation depending on the type of subjects recruited. Hence the question of the effects of tactile stimulation provided by compression garments on postural control remains open particularly in young subjects where sporting experience seems to modulate the responses. We therefore analysed the effects of compression garments on the postural control of young active subjects and high-level athletes. Our results showed that there was a high degree of variability in responses within each of these two samples of participants. Statistical analyses of hierarchical clustering allowed us to identify subgroups of individuals who responded differently to compression in these two types of subjects. The ability of participants to benefit from compression garments appears to be related to their initial balancing abilities and/or their preferred sensorimotor strategies.

Key words: postural control, compression garments, posture, inter-individual variability, sensorimotor strategy