Neurophysiologie Clinique/Clinical Neurophysiology (2015) 45, 285—295

ELSEVIER MASSON

Disponible en ligne sur
ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com/en

REVIEW/MISE AU POINT

Which biomechanical models are currently used in standing posture analysis?

Quels sont les modèles biomécaniques utilisés actuellement en analyse de la posture debout ?

A. Crétual [a,b,*]

[a] *M2S lab (Mouvement Sport Santé), University Rennes 2 — ENS Rennes — UEB, avenue Robert-Schuman, campus de Ker Lann, 35170 Bruz, France*
[b] *MimeTIC team, INRIA Rennes, campus universitaire de Beaulieu, 35042 Rennes, France*

Received 17 July 2015; accepted 23 July 2015
Available online 18 September 2015

KEYWORDS
Posturography;
Center of pressure;
Center of mass;
Segmental models;
Postural control

Summary In 1995, David Winter concluded that postural analysis of upright stance was often restricted to studying the trajectory of the center of pressure (CoP). However, postural control means regulation of the center of mass (CoM) with respect to CoP. As CoM is only accessible by using a biomechanical model of the human body, the present article proposes to determine which models are actually used in postural analysis, twenty years after Winter's observation. To do so, a selection of 252 representative articles dealing with upright posture and published during the four last years has been checked. It appears that the CoP model largely remains the most common one (accounting for nearly two thirds of the selection). Other models, CoP/CoM and segmental models (with one, two or more segments) are much less used. The choice of the model does not appear to be guided by the population studied. Conversely, while some confusion remains between postural control and the associated concepts of stability or strategy, this choice is better justified for real methodological concerns when dealing with such high-level parameters. Finally, the computation of the CoM continues to be a limitation in achieving a more complete postural analysis. This unfortunately implies that the model is chosen for technological reasons in many cases (choice being a euphemism here). Some effort still has to be made so that bioengineering developments allow us to go beyond this limit.

* Correspondence. M2S lab (Mouvement Sport Santé), University Rennes 2 — ENS Rennes — UEB, avenue Robert-Schuman, campus de Ker Lann, 35170 Bruz, France.
E-mail address: armel.cretual@univ-rennes2.fr

http://dx.doi.org/10.1016/j.neucli.2015.07.004
0987-7053/

MOTS CLÉS
Posturographie ;
Centre de pression ;
Centre de masse ;
Les modèles segmentaires ;
Le contrôle postural

Résumé En 1995, David Winter faisait remarquer que l'analyse de la posture quasi statique debout était souvent réduite à l'étude de la trajectoire du centre de pression (CdP). Pourtant, le contrôle postural consiste en la régulation du centre de masse (CdM) par rapport au CdP. Comme le CdM ne peut être estimé qu'à travers l'utilisation d'un modèle du corps humain, cet article propose de déterminer quels sont les modèles utilisés en analyse posturale vingt ans après l'observation faite par Winter. Pour cela, une sélection représentative de 252 articles traitant de la posture debout et publié lors des quatre dernières années a été étudiée. Il apparaît que le modèle n'utilisant que le CdP reste largement majoritaire (près des deux tiers de la sélection). Les autres modèles, CdP/CdM ou segmentaires (avec un, deux ou plus de segments) sont nettement moins utilisés. Ce choix du modèle ne semble pas guidé par le type de population étudiée. À l'inverse, même s'il existe toujours des confusions entre le contrôle postural et des concepts qui lui sont associés tels que stabilité ou stratégie, le choix du modèle est mieux justifié d'un point de vue méthodologique lorsqu'il s'agit d'évaluer ces paramètres de plus haut niveau. Enfin, le calcul du CdM continue à être une limite pour parvenir à une analyse posturale plus complète. Cela implique que le modèle est en réalité souvent choisi pour des questions technologiques (choix étant alors un euphémisme). Des efforts restent donc à fournir pour que les développements en bio-ingénierie permettent de dépasser cette limite.

Introduction

The maintenance of quiet standing in humans has been the subject of numerous publications over many years, from the beginning of the 20th century onwards. From a mechanical point of view, this task is quite a simple one to study. Only two forces are involved: the weight and the ground reaction force. Their points of application are respectively the center of gravity (CoG), which is identical to the center of mass (CoM), and the center of pressure (CoP). As the weight of a given subject remains constant, only the evaluation of the ground reaction force is needed, from the forces point of view. Nevertheless, as explained by Stoffregen and Riccio in 1988 [84] and recalled by Winter in his consistently cited review article on human balance [90], this situation is not stable, since any horizontal displacement of the CoM with respect to the CoP will create a torque that will increase this displacement and therefore lead to falling if nothing is done to counterbalance it. Thus, owing to this mechanically unstable situation, quiet standing needs a permanent control of CoP and CoM relative positions, such that the distance between CoP and the projection of CoM onto the horizontal plane remains on average equal to zero. The position of the CoP can be modified through the distribution of plantar pressures; whereas CoM is modified by displacements of one body part relative to others. Let us denote that this zero-mean distance is only a necessary condition. Due to a restricted margin of stability, the length of the temporal interval during which this zero-mean condition must be respected is actually very short. These spatial and temporal margins of stability are indeed narrower than the one identified by Hof et al. [49] as they consider the excursion of the CoP or the CoM independently one from the other with respect to the convex hull of the feet (or possibly one single foot).

A complete kinetic study of human standing posture would therefore need to consider both CoM and CoP. This implies measuring or estimating these through computation from indirect measurement. It is well known that none of them is an anatomical point. Position of the CoP is quite easily accessible through measurements provided by pressure mapping sensors or, more usually in posturography, through ground reaction force and torques obtained from a forceplate. The CoM position is a bit more complex to estimate. It has to be computed by taking into account relative motions of each part of the body in relation to each other, proportionally to their masses. An ideal measurement would be some kind of real-time MRI giving the position of any voxel of the body as well as its composition, to be able to retrieve its mass. Unfortunately, such a device does not as yet exist. The computation of CoM position obviously needs to rely on a simplification of body representation. The most common way to do so in biomechanics is to consider the body as a set of rigid segments (first approximation) that are articulated one with respect to the previous one in the kinematics chain through perfect joints (second approximation) [92]. Consequently, studying a person's posture or movement (succession of postures) essentially means providing the joint angles. With the hypothesis of rigid segments, it follows that the center of mass of each segment is stationary with respect to its two extremities. Therefore, knowing the mass of all body segments allows computation of the global CoM as a weighted sum of each segment's center of mass. Even if some methods are proposed to have access to individual values of inertia parameters [25], the most current process is based on anthropometric tables [29]. This computation has been validated, comparing CoM acceleration to what can be obtained from forceplate measurement [59]. Even if the widely accepted ISB recommendations for the joint angles computation of joint angles for lower [93] and upper body [94] are still debated, and some improvements are regularly proposed (for example for the shoulder [53] or the shank [22]), the principle of the articulated rigid bodies model is never questioned.

Anyone interested in biomechanical analysis of human motion agrees that the very usual 14-segments model can be modified depending on the movement that is actually studied, as recalled by Winter in his reference book [91].

Indeed, in the case of quiet standing, much simpler models are often used. The simplest one encountered is not even segmental; it is limited to one single point, the CoP. However, in 1995, Winter denoted that ''in the literature, there is a major misuse of the CoP when it is referred to as 'sway', thereby inferring that it is the same as the CoG'' and he even added that ''some researchers even refer to the CoP directly as the CoG'' [90]. Indeed, as explained by Winter, sway must refer to the relative position of the CoM with respect to the CoP. By itself, CoP is insufficient to study postural control that must be seen as CoM sway with respect to CoP.

Without actually estimating CoM, Horak and Nashner proposed to study the control of disturbance rejection (i.e. a sudden backward or forward motion of the support platform) [50] by defining the ankle and hip strategies. The first one corresponds to a single inverted pendulum movement articulated at the ankle while the second one corresponds to a double inverted pendulum articulated both at the hip and the ankle. The analysis of postural control can be performed using simpler models, such as solely single segment model [55] or more elaborate models, such as multi-segments [21].

Twenty years after the observation made by Winter about the overuse of the CoP model, the first and main goal of this bibliographical study is to evaluate which models are currently used in the analysis of human upright posture. To do so, a statistical analysis of the four last years' scientific literature within this wide scope has been conducted. For clarity's sake, two remarks must be made. First, this study is not a systematic review as the point is not to provide a meta-analysis on the results but only focuses on article methodology. In addition, some vocabulary confusions occur too regularly in the clinical and biomechanical scientific communities. To avoid this issue later on in the article, ''posture'' will always be used as referring to segmental organization; thus, neither ''posture'' nor ''sway'' will mean CoP displacement.

The second goal of this study is to evaluate whether the variability of the choice of the model could be due to certain potential factors. One of the most evident ones is the population studied whose varying parameters are age or the presence of pathology. Obviously, it will not be possible to make an exhaustive analysis of the influence of any specific pathology that could affect postural control and only a few examples will be highlighted. The aim is that those examples are sufficiently representative to be in order to discuss the potential link between the choice of the model and a given pathology. Finally, as explained by Haddad et al., postural control can be — or rather should be — studied with higher level parameters that are well known in control theory, such as perturbation rejection in the case of dual tasking, stability or control strategy [42].

Statistical analysis of recent bibliography

Article selection

In order to have a sufficiently large and representative set of articles dealing with the biomechanical analysis of upright standing available, the following multi-criteria research was performed on PubMed: ''(posture OR postural) AND (stance OR standing OR balance OR sway)''. Several complementary filters were added. First of all, as we are interested in the current state-of-the-art, research was restricted to articles published since January 2011. Only the original studies were taken into account and consequently the ''review'' articles were excluded. The research was also obviously restricted to the human species. Finally, to ensure readability and potential fast rejection articles had to be written in English and an abstract had to be available. The first selection led to 4884 articles. To reduce this very large amount, a random sub-selection of one article out of 6 was performed, leading to 814 articles that were checked. For want of exhaustiveness, this random selection provided a reasonable number of articles to ensure a representative sample.

These 814 articles were not all relevant. First of all, some of them (75, i.e. 9.2%) were off topic — for example, dealing with blood pressure, cardiology, very young children (less than 9 months), orthopaedics of spine, etc. The articles considered were required to deal with maintaining an upright posture without changing the supports, as presented in Fig. 1. Apart from obvious bipedal quiet standing, this also includes unipodal stance and perturbation rejection of these two conditions. Conversely, many articles concerned with upright posture actually deal with motion from or to this condition, such as gait initiation, post-jump stabilization, sit-to-stand, etc. Among the 739 remaining articles, 199 additional ones (24.4% of the initial set) had to be removed since they were only interested in such movements. Let us denote that several articles can deal with upright standing and some other movement, such as gait. If the analysis of upright standing was independent from the other motion, such articles were kept in the selection until the last step.

Finally in many articles (288 i.e. 35.4%), no biomechanical model was used. Generally, in these articles, the postural evaluation is performed using clinical tests that do not imply objective biomechanical measurement, such as Berg Balance Test, Fullerton Advanced Balance Scale, Balance Evaluation Systems Test, Star Excursion Balance Test, etc. At the end, 252 articles (31.0% among the 814 initial ones) actually used a biomechanical model and were therefore retained for analysis. One side result of this selection is that bioengineering journals are slightly more prone to publish articles with models than clinical ones. Although no statistics have been made regarding this specific point, as those two sets of journals cannot precisely be defined, this nevertheless shows a potential discrepancy between development of valuation methods and their actual application in clinical routine. The complete list of these 252 articles is provided as Supplementary data.

Models used

The statistical analysis consisted of classifying these articles depending on the biomechanical model they are based on. First of all, let us emphasize that model does not mean marker set. Model refers to how the human body is represented in a simplified manner; it is a qualitative definition. Each model has parameters that account for the potential evolution of body movements in this simplified representation. The step consisting of retrieving those parameters, i.e. making a quantitative estimation of the model is called identification. Identification is usually performed using a

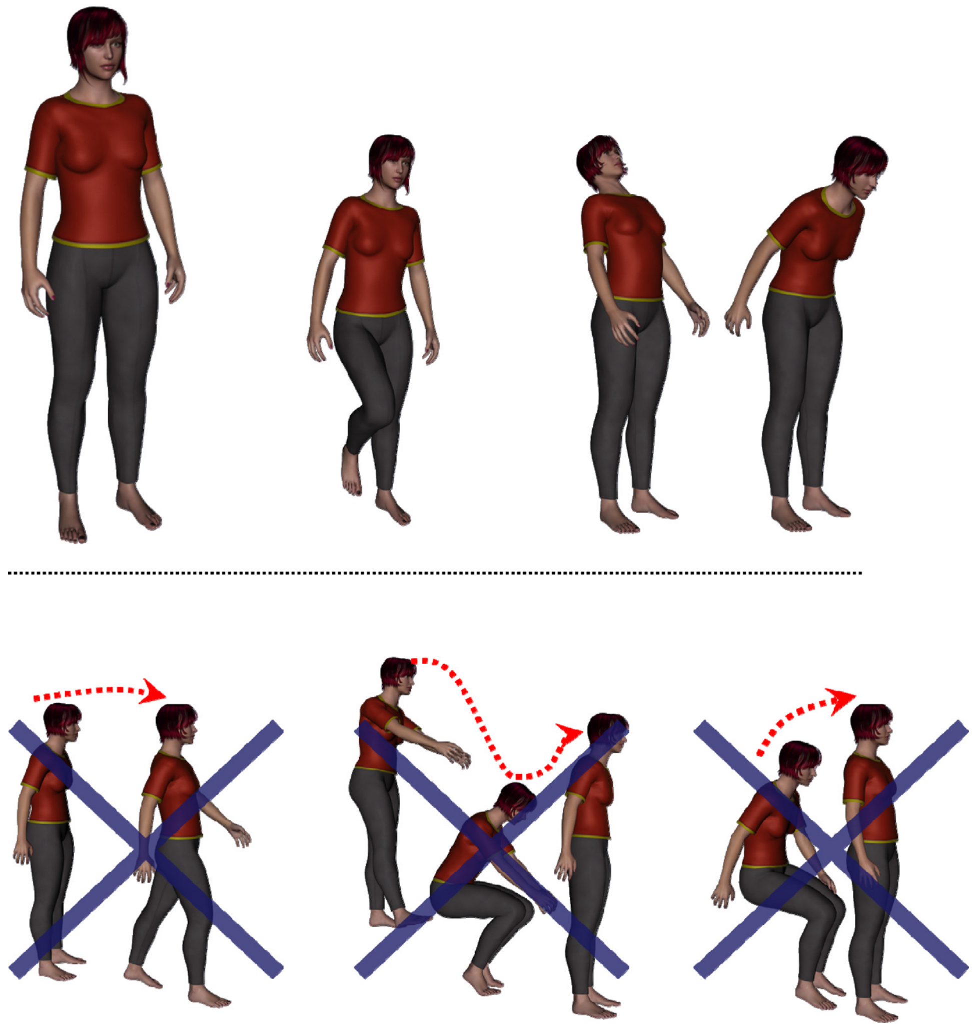

Figure 1 Situations considered (top, from left to right: quiet standing on both feet, monopodal stance and perturbation rejection of those situations while maintaining the same contacts on the floor) and examples of conditions excluded as implying a modification of supports (bottom, from left to right: gait initiation, post-jump stabilization, sit-to-stand).

measurement process and identification is different from, albeit complementary to, modelling. It is only at this step that a marker set could be needed if the measurement device is based on video technology. Let us consider the example of the single inverted pendulum in the sagittal plane, i.e. the body seen as one straight line. Such a model would then have one parameter: the angle between this line and the vertical. In the case of video measurement, the marker set would potentially be one marker on the ankle joint and another one on the top of the head. For the same model (one single line for the whole body), alternative marker sets could be used (e.g. shoulder joints instead of head). When the measurement is not performed through video but from a device, such as an inclinometer, there might even be no marker set at all for the same model.

The models considered in our meta-analysis are presented in Fig. 2. Six categories were taken into account: CoP alone, CoM alone, CoP and CoM, single pendulum, double pendulum and multi-segments. The terms ''point-like models'' and ''segmental models'' will respectively refer to the first three and latter three categories.

Moreover, within each of these categories, the model can be restricted to one anatomical plane (the sagittal or frontal one) or, on the contrary, include both planes. More precisely, the point is to know whether only one or both horizontal directions, i.e. antero-posterior (AP) and medio-lateral (ML), are considered in the model. Indeed, in the case of the CoP alone model, the analysis is best performed in the horizontal plane, but could however be done in both AP and ML directions. From now on, the terms ''unidirectional'' or ''bidirectional'' will respectively refer to models considering only one of the two horizontal direction, or both of them.

Finally, let us denote that concerning more specifically the single pendulum model, there is no consensus about which angle is actually represented. As explained on Fig. 3, it could be the anatomical ankle joint angle or the angle between the vertical and a line representing the mean body orientation. In this second case, it could sometimes be the line going from the ankle joint to the top of the head or at other times, the CoP-CoM line. In this latter case, the choice between ''CoP/CoM'' and ''simple pendulum'' categories

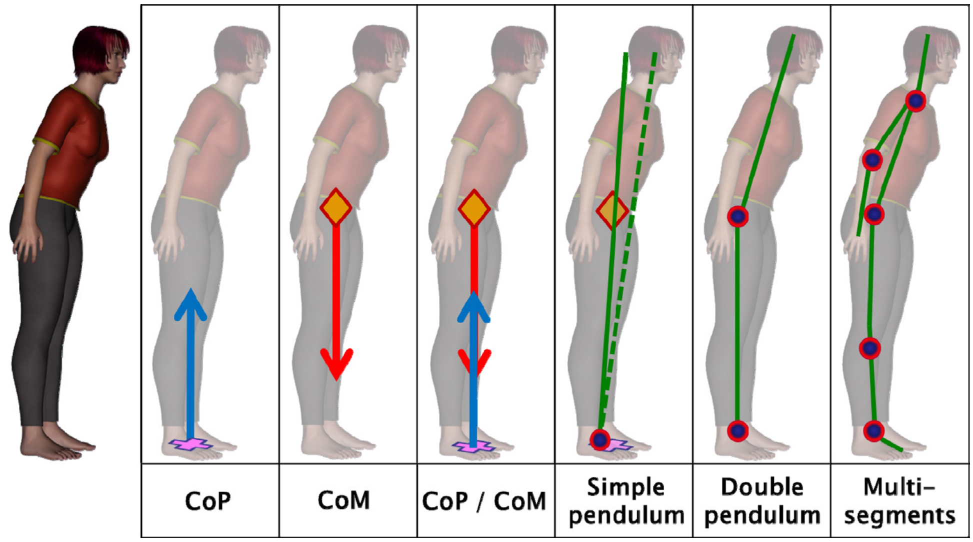

Figure 2 Different models used in postural analysis. From left to right: Center of Pressure alone (CoP), Center of Mass alone (CoM) Center of Pressure and Center of Mass (CoP/CoM), single pendulum, double pendulum and multi-segments.

could be potentially ambiguous. The pertinent criterion is whether the study focuses on the angle or not. However, despite all these remarks, from now on, the kind of angle studied within the simple pendulum category will not be highlighted. Indeed, the underlying model is the same in all these cases.

Results

The statistical results of the classification are provided in Table 1.

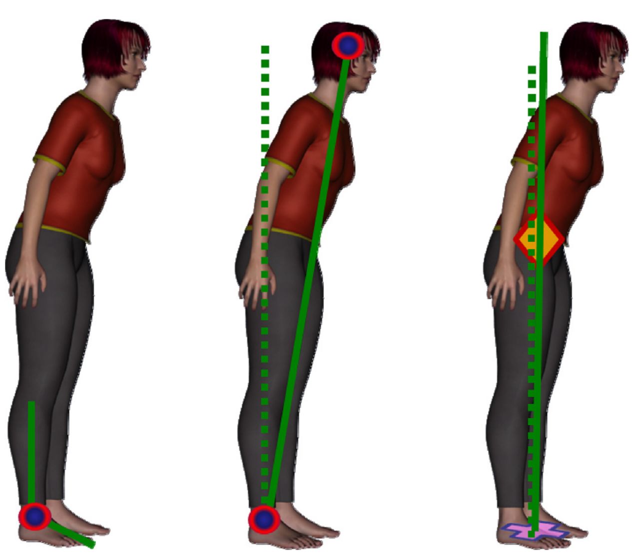

Figure 3 Three different angles that could be considered in the single pendulum model. From left to right: the ankle joint angle, the angle between vertical axis and the longitudinal axis of the body (i.e. the line passing through ankle joint angle and top of the head) or the angle between vertical axis and the CoP-CoM line.

First of all, it clearly appears that the simplest model (CoP alone) largely remains the most often used in biomechanical analysis of human standing posture. It represents almost two thirds of the articles of the selection. On the other hand, the CoM model is hardly ever encountered. More surprisingly, the double pendulum model is noticeably less employed than each of the two other segmental models. Finally, models are much often bidirectional. This has however to be moderated for segmental models, particularly for double pendulum ones for which unidirectional models are usual.

Discussion

Mono- or bidirectional models

From a global point of view, unidirectional models are encountered in only 17.4% of the articles (44/252). However, there is a discrepancy between point-like models and segmental ones. The percentage of unidirectional models falls to 6.0% in the first set (only 9 articles upon 167). On

Table 1 Distribution of the 252 articles in the six categories of biomechanical models.

Model	Number of articles/and percentage	Number of articles with unidirectional/bidirectional models
CoP	161 (63.9%)	9/152
CoM	6 (2.4%)	1/5
CoP/CoM	19 (7.5%)	2/17
Simple pendulum	24 (9.5%)	10/14
Double pendulum	14 (5.6%)	10/4
Multi-segments	28 (11.1%)	12/16

the contrary, in nearly half (48.5%, 32/66) of the latter set, the model is only considered in one of the two possible vertical planes, usually the sagittal one (27/32). It can however be noticed that the frontal plane is considered for some specific populations where asymmetry has to be evaluated, such as in hemiparesis [7], adolescents with idiopathic scoliosis [3] or in the case of a modified perceptual vertical gravity line [38]. The ratio between uni- or bidirectional models is most dissimilar in the case of the double pendulum model, as only four bidirectional models are encountered versus 10 unidirectional ones.

Over-representation of CoP model

In the great majority of the 161 studies based on CoP model, CoP displacement and the parameters that they are usually extracted from (range, surface, etc.), appear to be sufficient to distinguish groups or to prove the effect of some given intervention. However, it is certainly notable, despite the observation of Winter in 1995 about the confusion at that time between CoP and sway, that within this set, the word ''sway'' is still used as being synonymous with CoP displacement. For example, 113 articles (70.2%), referred to ''sway surface'', to account for the 95% ellipse of CoP positions. It is regrettable that the seemingly high percentage of CoP model studies seems to be mainly explicable by this continued confusion between the words ''posture'', ''sway'' and ''CoP displacement''. Moreover, it has been shown that even if numerous stability parameters have been developed from CoP measurement, it seems that they indeed provide some very similar information [78]. The other main reason for this over-representation is that CoP is much more accessible to measurement than are CoM and segmental motions. This point will be discussed later on; but unfortunately, it has to be concluded that very often the CoP model is chosen not because of methodological reasons but because of technological limitations.

However, in several cases, restricting analysis to the CoP displacement is questionable, as when the goal is to determine the effect upon posture of a stimulation, voluntary or not, on one given joint and when no evaluation is carried out of the joint itself. When concluding that electrical stimulation of one knee joint stabilizes posture [58], it would be worth checking whether this is due to a diminished knee joint motion. Similarly, when studying postural control in the presence of neck pain [77], upper body posture evaluation would help, as it has been previously demonstrated that the simple fact of bending the head forward can have an effect on CoP displacement, even in healthy subjects [83]. In the same way, in many studies, the goal is to assess the consequence of a modified kinematics or kinetics condition. It would have been interesting to know how the trunk posture of children with backpack carriage was modified as an adaptation to load increase [76]; or of women with breast hypertrophy, who exhibit larger CoP displacements compared to normal breasted women [4]. In the analysis of the influence of wearing high heels, knowing how women compensate ankle hyperextension induced by 7 cm heels would be a valuable complementary inquiry to observation of increasing CoP displacement [36]. Finally, no actual evaluation of postural adaptations is made when linking body mass index and posture [61] or in the concomitant presence of obesity and severe knee osteoarthritis [48].

Nevertheless, when enriched through adequate signal processing, CoP raw data provide interesting parameters. For example, these can exhibit some distinguishable signatures of different movements while standing on both feet [82]. The fractal dimension and entropy of CoP trace are discriminant parameters in Down syndrome patients compared to control subjects [79]. Time-to-contact, meaning the time it would take for the CoP to reach the base of support boundaries given its current velocity, is an interesting parameter to account for stability [89]. Non-linear analysis through recurrence quantification analysis provides some useful complementary information [2].

Nevertheless, CoP model is not the only one used as 36.1% of the studies within the set of 252 articles are based on more elaborate models. Subsequently, we have tried to investigate which criteria lead to the choice of model. The potential influence of the population studied is discussed. Next, thinking laterally about this issue, we will focus on the influence of investigating some high-level parameters of postural control (dual tasking, stability and strategy).

Population

The choice of model is hardly ever justified by the specific concerns of a given population. Because the characteristics of the population are highly variable, it is quite impossible to pretend to be exhaustive. It remains possible to try to illustrate this assessment by focusing on two different populations quite frequently observed in the set of 252 articles: adolescents with idiopathic scoliosis and the elderly. Even if statistics performed within these subsets would be of arguable value due to their limited extent, it seems that all models are currently used within each subset in similar proportion to the complete set. However, let us add that this is not always the case. In contrast to this global result, it is notable that in any of the 17 articles dealing with stroke or hemiparesis, the biomechanical model used is always the CoP alone. Let us finally insist on the fact that these three samples remain examples of the meta-analysis.

Idiopathic scoliosis

Posture of adolescents with idiopathic scoliosis can be studied with CoP alone, whether exploring Time-to-contact to base of support boundaries [40] or the influence of a surgical treatment, [27]. The CoP/CoM model is used to evaluate the link between trunk posture and Cobb angle [24]. Finally, multi-segment model allows the evaluation of proprioceptive information in sensory integration [3] or the reliability of clinical postural indices [34]. Let us denote that in this last case, the question is actually posture and not its control, since only the mean segmental organization is considered and not the concomitant regulation of CoM and CoP to maintain upright stance.

Elderly

Elderly subjects constitute an often-investigated population in posture analysis. In those numerous studies, CoP model is used to evaluate the role of vision and proprioception

[5]; the influence of being in the rear limit of base of support since rear falls are more frequent [46]; the link with a functional index of autonomy [30]; or the association with systolic blood pressure during moderate exercise [67]. The CoP model can help to see whether age is a worsening factor in case of sleep deprivation [80], upon anticipatory and compensatory movements in lateral perturbation [19] or in response to standing on altered surfaces [60]. This model also allows quantification of the effects of an 8-week period program [1], or two weeks' bed rest [81].

The CoP/CoM model has been considered to measure the effects of a visual memory task [6] or to verify if the anticipatory soleus contraction effect is maintained in the elderly [70] even if in that latter study, CoM is estimated as the displacement of the third lumbar vertebra.

The simple pendulum enables to check whether elderly drivers rated as unsafe have a larger sway, seen as the horizontal displacement of the waist [62]. It is also used to propose a model of neural control of small perturbation rejection and the influence of the subject's age on its parameters [26]. Working with the double pendulum allows demonstration that movements between lower and upper body are less in antiphase in the elderly [56]; and to measure the immediate effect of an ankle foot orthosis in this population [1]. Finally, a multi-segments model can be used to evaluate the combined effect of obesity and age [16], or to assess how the response to a smooth antero-posterior displacement of the support plate is less efficient in the elderly [86].

Hemiparesis and stroke

While the CoP model is the only one observed in the 17 studies concerned with hemiparetic patients, 14 are in both planes and 3 in the frontal plane only. It is also notable that in 8 of these studies, two force plates are used, i.e. one under each foot. This allows a finer estimation of medio-lateral asymmetry [10,69]. Apart from two other studies dealing with Parkinson's disease patients [37] or unilateral amputees [23], such an apparatus is nearly never observed in other populations, despite the fact that asymmetry could be a reasonable concern in scoliotic children [24] or in lower leg amputee subjects [73].

Even if CoP trajectory asymmetry is better analyzed through a double forceplate device, considering in fact the CoP trace under each foot, it is astonishing that no study appears in that set whose goal is to evaluate the actual postural asymmetry, meaning the segmental organization of the hemiparetic patient in the frontal plane.

High-level parameters of postural control

From a global point of view, studying how a dynamic system is controlled commonly means evaluating how this system reacts when perturbed. In the maintaining of an upright stance, this can be done through the analysis of dual task situations, the first task being the stance itself and the other one being a potential perturbation. Another recurring question is the evaluation of stability, i.e. for such a mechanically unstable system stabilized through neuromuscular actions to quantify the bounds within which some given state variables have to remain. Finally, as CoM position has to be permanently controlled, a frequent concern is to study the postural strategies used to do so.

Dual task

It can be noted that whatever the type of secondary task, whether it is a reaction task or an increase of cognitive load, the CoP model is nearly the only one encountered in the articles dealing with dual tasking. Reaction task can be auditory [8] or visual [31,45]. Cognitive load increase can take various forms: speaking in whiplash patients [68]; an auditory-memory task in blind persons [72]; a reading task in dyslexic children [66]; counting backward [74] or word list generation [88] in patients with multiple sclerosis; or audio-visual distraction in post-stroke patients [13]. Interestingly, one study shows that newly standing children have an improved postural control, seen as a reduced CoP displacement, when holding a toy in their hands [20].

Stability

Many studies use the word ''stability'' as a synonym of ''postural control'' and even of ''CoP control'', making the assumption that lower CoP displacement signifies better stability, which is inexact. This confusion exists in the analysis of the influence of impaired hearing [28]; light touch [35]; anxiety [39]; neck torsion in whiplash patients [96]; competitive match in soccer players [15]; and shoe design in patients with rheumatoid arthritis [14]. Yet, the double pendulum model is used to evaluate postural stability in ankle-injured athletes [52] but in pure quiet stance only, i.e. not really quantifying stability.

In two studies where a CoP/CoM model is mentioned but in which CoM is actually computed as low-pass filtering of CoP, which remains questionable, a true stability evaluation is performed. The first uses a retropulsion test (unfortunately not described) and the ratio between CoP and CoM path lengths to quantify stability [9]; while the other explores the best-fitting ellipse of CoM trajectory when subjects bring their CoP to the maximal distance from the middle of their feet in each direction [33]. Using only CoP measurement, limits of stability can be assessed as the maximal displacement of CoP before losing stability, i.e. having to modify at least one foot position to avoid falling. This interesting parameter has been encountered to evaluate the effect of balance training using virtual reality in elderly [32], the influence of knee or ankle immobilization [54] or the ability of cerebral palsy children to reject the perturbation induced by arm raising [64]. A multi-segments model is employed to explore the influence of low-back pain on monopodal posture and to estimate stability through two indices: kinetic, based on ground force; and kinematic, based on segment orientation [65].

Finally, one article proposes a genuine stability analysis of upright stance using non-linear methods of dynamical systems exploration and is based on a simple pendulum model [17]. This theoretical model still needs to be experimentally validated, in particular as it assumes that CoM displacement can be fully predicted from ankle joint motions.

Strategy

In two articles mentioning strategy, but where this means in fact classical postural analysis (since no ''strategy'' parameter is defined or used), the CoP model is employed [18,51].

Not surprisingly, following Horak and Nashner's proposal [50], the most common model used when really dealing with postural strategy is the double inverted pendulum, often restricted to the sagittal plane. Indeed, some theoretical and very detailed controller models have been proposed, one allowing demonstration that the control scheme of the double pendulum is possibly intermittent rather than continuous [85], and a second one based on optimal control theory [11]. Though very promising, both of these models are still to be validated through comparison to real data. The double pendulum has also been used to study control from sensory feedback [47], to evaluate postural strategy in Parkinson's disease subjects [12] or coordination in ballet dancers [57]. Finally, it should be noted that one article uses a slightly more complex model to examine phase synchronization in a three segments model, also considering the knee [41].

Conclusion

Twenty years after Winter's comment about CoP displacement and postural control being too often confused, it is unfortunately still to be noted that the CoP model remains predominant. Most articles would be clearer if the authors would simply talk about ''CoP displacement'' when referring to this parameter, being truly linked to postural control, but only a partial view of this control. At the time that Winter wrote his article, this could be explained by technological limitations. Unfortunately CoP displacement became synonymous with postural control due to the fact that, in the 1990s, technology was hardly able to measure parameters other than CoP. However in the current technological era, the biomechanical and clinical community now needs to break out of this vicious circle.

Indeed, in 1996, Hasan et al. observed that ''the reason the CoM is frequently ignored is that it cannot be measured directly, whereas the CoP is readily obtained from a force platform'' [43,44]. They added that ''independent, simultaneous measurements of the CoP and CoM are a necessary step towards characterizing their relationship''. Unfortunately, CoM is sometimes still estimated through a simple low-pass filtering of CoP [75]. However, this assumption came from comparing low-pass filtering of CoP to an approximation of CoM, the weighted sum of segment CoM and not the real CoM. Such an approximation method is known to act as a low-pass filter; moreover usually after a first low-pass filtering of raw 3D data. The actual frequency spectrum of the CoM is probably greater than what is retrieved through low-pass filtering of CoP.

A first step to get a better estimation of CoM is to use all the data provided by the forceplate. Indeed, even if, as seen above, only the CoP position is usually considered, the ground reaction force is also available, which very easily allows computation of the CoM's acceleration. The double integration then needed to estimate its position is not trivial, but the combination of ground reaction force and CoP can lead to an acceptable estimation of CoM position [97]. By comparing three methods, weighted sum of segmental motions, double integration of ground force and low-pass filtering of CoP, it has been shown that there could be a small but effective discrepancy between low-pass filtering and the two other methods [63]. A promising approach proposes to estimate CoM position through a combination of kinematics and dynamics measurements, taking advantage of both [71]. Unfortunately, the use of precise 3D human motion measurement devices is not yet fully feasible or at least widespread in clinical routine, due to device costs and the subject preparation that is often needed. Some preliminary results of body segment motion measures in upright stance using simpler and cheaper devices have recently been published [87,95]. Even if by definition upright stance implies small range motions, and thus an unappreciable signal/noise ratio, the combination of such measures and the ground reaction force in an optimization method could be a valuable solution.

A necessary milestone to reach is thus that such bioengineering development in posturography must now be made accessible to clinicians, so that a complete evaluation of postural control, i.e. CoM and CoP, can be performed in routine practice.

Disclosure of interest

The author declares that he has no conflicts of interest concerning this article.

Acknowledgement

The author would like to thank Pr. Isabelle Bonan (CHU de Rennes) and the *Société francophone posture équilibre locomotion* (SOFPEL) for submitting the question that became the subject of this article.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.neucli.2015.07.004.

References

[1] Alfieri FM, Riberto M, Abril Carreres À, Boldó, Castellet, Figuera LR, et al. Effectiveness of an exercise program on postural control in frail older adults. Clin Interv Aging 2012;7:593—8.

[2] Apthorp D, Nagle F, Palmisano S. Chaos in balance: non-linear measures of postural control predict individual variations in visual illusions of motion. PLoS One 2014;9(12):e113897.

[3] Assaiante C, Mallau S, Jouve J-L, Bollini G, Vaugoyeau M. Do adolescent idiopathic scoliosis (ais) neglect proprioceptive information in sensory integration of postural control? PLoS One 2012;7(7):e40646.

[4] Barbosa A, Raggi G, Sa C, Costa M, Lima Jr J, Tanaka C. Postural control in women with breast hypertrophy: postural control in breast hypertrophy. Clinics 2012;67(7):757—60.

[5] Baudry S, Duchateau J. Age-related influence of vision and proprioception on ia presynaptic inhibition in soleus muscle during upright stance. J Physiol 2012;590(21):5541—54.

[6] Berger L, Bernard-Demanze L. Age-related effects of a memorizing spatial task in the adults and elderly postural control. Gait Posture 2011;33(2):300—2.

[7] Bingham JT, Choi JT, Ting LH. Stability in a frontal plane model of balance requires coupled changes to postural configuration and neural feedback control. J Neurophysiol 2011;106(1):437—48.

[8] Bisson EJ, McEwen D, Lajoie Y, Bilodeau M. Effects of ankle and hip muscle fatigue on postural sway and attentional demands during unipedal stance. Gait Posture 2011;33(1):83—7.
[9] Blaszczyk JW, Orawiec R. Assessment of postural control in patients with parkinson's disease: sway ratio analysis. Hum Mov Sci 2011;30(2):396—404.
[10] Bonan I, Marquer A, Eskiizmirliler S, Yelnik A, Vidal P-P. Sensory reweighting in controls and stroke patients. Clin Neurophysiol 2013;124(4):713—22.
[11] Bonnet V, Ramdani S, Fraisse P, Ramdani N, Lagarde J, Bardy BG. A structurally optimal control model for predicting and analyzing human postural coordination. J Biomech 2011;44(11):2123—8.
[12] Boonstra TA, Schouten AC, van der Kooij H. Identification of the contribution of the ankle and hip joints to multi-segmental balance control. J Neuroeng Rehabil 2013;10(1):23.
[13] Bourlon C, Lehenaff L, Batifoulier C, Bordier A, Chatenet A, Desailly E, et al. Dual-tasking postural control in patients with right brain damage. Gait Posture 2014;39(1):188—93.
[14] Brenton-Rule A, D'Almeida S, Bassett S, Carroll M, Dalbeth N, Rome K. The effects of sandals on postural stability in patients with rheumatoid arthritis: an exploratory study. Clin Biomech 2014;29(3):350—3.
[15] Brito J, Fontes I, Ribeiro F, Raposo A, Krustrup P, Rebelo A. Postural stability decreases in elite young soccer players after a competitive soccer match. Phys Ther Sport 2012;13(3):175—9.
[16] Carneiro J, Santos-Pontelli T, Vilaca K, Pfrimer K, Colafemina J, Carneiro A, et al. Obese elderly women exhibit low postural stability: a novel three-dimensional evaluation system. Clinics 2012;67(5):475—81.
[17] Chagdes JR, Rietdyk S, Jeffrey MH, Howard NZ, Raman A. Dynamic stability of a human standing on a balance board. J Biomech 2013;46(15):2593—602.
[18] Cimolin V, Galli M, Vismara L, Grugni G, Priano L, Capodaglio P. The effect of vision on postural strategies in Prader-Willi patients. Res Dev Disabil 2011;32(5):1965—9.
[19] Claudino R, dos Santos EC, Santos MJ. Compensatory but not anticipatory adjustments are altered in older adults during lateral postural perturbations. Clin Neurophysiol 2013;124(8): 1628—37.
[20] Claxton LJ, Melzer DK, Ryu JH, Haddad JM. The control of posture in newly standing infants is task dependent. J Exp Child Psychol 2012;113(1):159—65.
[21] Clifford AM, Holder-Powell H. Postural control in healthy individuals. Clin Biomech 2010;25(6):546—51.
[22] Conti G, Cristofolini L, Juszczyk M, Leardini A, Viceconti M. Comparison of three standard anatomical reference frames for the tibia-fibula complex. J Biomech 2008;41(16):3384—9.
[23] Curtze C, Hof AL, Postema K, Otten B. The relative contributions of the prosthetic and sound limb to balance control in unilateral transtibial amputees. Gait Posture 2012;36(2): 276—81.
[24] Dalleau G, Leroyer P, Beaulieu M, Verkindt C, Rivard C-H, Allard P. Pelvis morphology, trunk posture and standing imbalance and their relations to the cobb angle in moderate and severe untreated ais. PLoS One 2012;7(7):e36755.
[25] Davidson PL, Wilson SJ, Wilson BD, Chalmers DJ. Estimating subject-specific body segment parameters using a 3-dimensional modeller program. J Biomech 2008;41(16): 3506—10.
[26] Davidson BS, Madigan ML, Southward SC, Nussbaum MA. Neural control of posture during small magnitude perturbations: effects of aging and localized muscle fatigue. IEEE Trans Biomed Eng 2011;58(6):1546—54.
[27] de Abreu DCC, Gomes MM, Santiago HARd, Herrero CFPdS, Porto MA, Defino HLA. What is the influence of surgical treatment of adolescent idiopathic scoliosis on postural control? Gait Posture 2012;36(3):586—90.
[28] De Kegel A, Dhooge I, Cambier D, Baetens T, Palmans T, Van Waelvelde H. Test-retest reliability of the assessment of postural stability in typically developing children and in hearing impaired children. Gait Posture 2011;33(4):679—85.
[29] de Leva P. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J Biomech 1996;29(9):1223—30.
[30] de Noronha Ribeiro Daniel F, de Souza Vale RG, Giani TS, Bacellar S, Escobar T, Stoutenberg M, et al. Correlation between static balance and functional autonomy in elderly women. Arch Gerontol Geriatr 2011;52(1):111—4.
[31] Derlich M, Krecisz K, Kuczynski M. Attention demand and postural control in children with hearing deficit. Res Dev Disabil 2011;32(5):1808—13.
[32] Duque G, Boersma, Loza-Diaz, Hassan H, Suarez, Geisinger, et al. Effects of balance training using a virtual-reality system in older fallers. Clin Interv Aging 2013;8:257—63.
[33] Forth KE, Fiedler MJ, Paloski WH. Estimating functional stability boundaries for bipedal stance. Gait Posture 2011; 33(4):715—7.
[34] Fortin C, Feldman DE, Cheriet F, Gravel D, Gauthier F, Labelle H. Reliability of a quantitative clinical posture assessment tool among persons with idiopathic scoliosis. Physiotherapy 2012;98(1):64—75.
[35] Franzén E, Gurfinkel V, Wright W, Cordo P, Horak F. Haptic touch reduces sway by increasing axial tone. Neuroscience 2011;174:216—23.
[36] Gerber SB, Costa RV, Grecco LAC, Pasini H, Marconi NF, Oliveira CS. Interference of high-heeled shoes in static balance among young women. Hum Mov Sci 2012;31(5):1247—52.
[37] Geurts A, Boonstra T, Voermans N, Diender M, Weerdesteyn V, Bloem B. Assessment of postural asymmetry in mild to moderate parkinson's disease. Gait Posture 2011;33(1): 143—5.
[38] Goodworth A, Chandan A, Chase H, Foster E, Francoeur H, Michaud J, et al. Stance width influences frontal plane balance responses to centripetal accelerations. Gait Posture 2013;37(1):98—102.
[39] Goto F, Kabeya M, Kushiro K, Ttsutsumi T, Hayashi K. Effect of anxiety on antero-posterior postural stability in patients with dizziness. Neurosci Lett 2011;487(2):204—6.
[40] Gruber AH, Busa MA, Gorton III GE, Van Emmerik RE, Masso PD, Hamill J. Time-to-contact and multiscale entropy identify differences in postural control in adolescent idiopathic scoliosis. Gait Posture 2011;34(1):13—8.
[41] Günther M, Putsche P, Leistritz L, Grimmer S. Phase synchronisation of the three leg joints in quiet human stance. Gait Posture 2011;33(3):412—7.
[42] Haddad JM, Rietdyk S, Claxton LJ, Huber JE. Task-dependent postural control throughout the lifespan. Exerc Sport Sci Rev 2013;41(2):123—32.
[43] Hasan SS, Robin DW, Szurkus DC, Ashmead DH, Peterson SW, Shiavi RG. Simultaneous measurement of body center of pressure and center of gravity during upright stance. Part i: methods. Gait Posture 1996;4(1):1—10.
[44] Hasan SS, Robin DW, Szurkus DC, Ashmead DH, Peterson SW, Shiavi RG. Simultaneous measurement of body center of pressure and center of gravity during upright stance. Part ii: amplitude and frequency data. Gait Posture 1996;4(1):11—20.
[45] Hegeman J, Nienhuis B, van den Bemt B, Weerdesteyn V, van Limbeek J, Duysens J. The effect of a non-steroidal anti-inflammatory drug on two important predictors for accidental falls: postural balance and manual reaction time. A randomized, controlled pilot study. Hum Mov Sci 2011;30(2): 384—95.
[46] Hernandez ME, Ashton-Miller JA, Alexander NB. Age-related changes in speed and accuracy during rapid targeted center of pressure movements near the posterior limit of the base of support. Clin Biomech 2012;27(9):910—6.

[47] Hettich G, Assländer L, Gollhofer A, Mergner T. Human hip-ankle coordination emerging from multisensory feedback control. Hum Mov Sci 2014;37:123—46.
[48] Hirata RP, Jørgensen TS, Rosager S, Arendt-Nielsen L, Bliddal H, Henriksen M, et al. Altered visual and feet proprioceptive feedbacks during quiet standing increase postural sway in patients with severe knee osteoarthritis. PLoS One 2013;8(8):e71253.
[49] Hof A, Gazendam M, Sinke W. The condition for dynamic stability. J Biomech 2005;38(1):1—8.
[50] Horak F, Nashner LM. Central programming of postural movements: adaptation to altered support-surface configurations. J Neurophysiol 1986;55(6):1369—81.
[51] Huisinga JM, Yentes JM, Filipi ML, Stergiou N. Postural control strategy during standing is altered in patients with multiple sclerosis. Neurosci Lett 2012;524(2):124—8.
[52] Huurnink A, Fransz DP, Kingma I, Verhagen EA, van Dieën JH. Postural stability and ankle sprain history in athletes compared to uninjured controls. Clin Biomech 2014;29(2):183—8.
[53] Jackson M, Michaud B, Tétreault P, Begon M. Improvements in measuring shoulder joint kinematics. J Biomech 2012;45(12): 2180—3.
[54] Jeon H-S, Hwang S, Woo Y-K. The effect of ankle and knee immobilization on postural control during standing. Knee 2013;20(6):600—4.
[55] Karlsson A, Lanshammar H. Analysis of postural sway strategies using an inverted pendulum model and force plate data. Gait Posture 1997;5(3):198—203.
[56] Kato T, Yamamoto S-I, Miyoshi T, Nakazawa K, Masani K, Nozaki D. Anti-phase action between the angular accelerations of trunk and leg is reduced in the elderly. Gait Posture 2014;40(1):107—12.
[57] Kiefer AW, Riley MA, Shockley K, Sitton CA, Hewett TE, Cummins-Sebree S, et al. Multi-segmental postural coordination in professional ballet dancers. Gait Posture 2011;34(1): 76—80.
[58] Kimura T, Kouzaki M. Electrical noise to a knee joint stabilizes quiet bipedal stance. Gait Posture 2013;37(4):634—6.
[59] Kingma I, de Looze MP, Toussaint HM, Klijnsma HG, Bruijnen TB. Validation of a full body 3-D dynamic linked segment model. Hum Mov Sci 1996;15(6):833—60.
[60] Kirchner M, Schubert P, Getrost T, Haas C. Effect of altered surfaces on postural sway characteristics in elderly subjects. Hum Mov Sci 2013;32(6):1467—79.
[61] Ku P, Abu Osman N, Yusof A, Wan Abas W. Biomechanical evaluation of the relationship between postural control and body mass index. J Biomech 2012;45(9):1638—42.
[62] Lacherez P, Wood JM, Anstey KJ, Lord SR. Sensorimotor and postural control factors associated with driving safety in a community-dwelling older driver population. J Gerontol A Biol Sci Med Sci 2014;69(2):240—4.
[63] Lafond D, Duarte M, Prince F. Comparison of three methods to estimate the center of mass during balance assessment. J Biomech 2004;37(9):1421—6.
[64] Ledebt A, Savelsbergh GJ. Postural adaptation during arm raising in children with and without unilateral cerebral palsy. Res Dev Disabil 2014;35(7):1782—8.
[65] Lee B-C, Martin BJ, Sienko KH. Directional postural responses induced by vibrotactile stimulations applied to the torso. Exp Brain Res 2012;222(4):471—82.
[66] Legrand A, Bui-Quoc E, Doré-Mazars K, Lemoine C, Gérard C-L, Bucci MP. Effect of a dual task on postural control in dyslexic children. PLoS One 2012;7(4):e35301.
[67] Maciaszek J, Stemplewski R, Osinski W. Effects of systolic blood pressure (sbp) on a postural stability in elderly men subjected to moderate exercise. Arch Gerontol Geriatr 2011;53(1):e37—40.
[68] Madeleine P, Nielsen M, Arendt-Nielsen L. Characterization of postural control deficit in whiplash patients by means of linear and nonlinear analyses - a pilot study. J Electromyogr Kinesiol 2011;21(2):291—7.
[69] Mansfield A, Danells CJ, Inness E, Mochizuki G, McIlroy WE. Between-limb synchronization for control of standing balance in individuals with stroke. Clin Biomech 2011;26(3):312—7.
[70] Masani K, Vette AH, Abe MO, Nakazawa K, Popovic MR. Smaller sway size during quiet standing is associated with longer preceding time of motor command to body sway. Gait Posture 2011;33(1):14—7.
[71] Maus H-M, Seyfarth A, Grimmer S. Combining forces and kinematics for calculating consistent centre of mass trajectories. J Exp Biol 2011;214(21):3511—7.
[72] Melzer I, Damry E, Landau A, Yagev R. The influence of an auditory-memory attention-demanding task on postural control in blind persons. Clin Biomech 2011;26(4):358—62.
[73] Nederhand MJ, Van Asseldonk EH, der Kooij vH, Rietman HS. Dynamic balance control (dbc) in lower leg amputee subjects; contribution of the regulatory activity of the prosthesis side. Clin Biomech 2012;27(1):40—5.
[74] Negahban H, Sanjari MA, Mofateh R, Parnianpour M. Nonlinear dynamical structure of sway path during standing in patients with multiple sclerosis and in healthy controls is affected by changes in sensory input and cognitive load. Neurosci Lett 2013;553:126—31.
[75] Ozdemir RA, Pourmoghaddam A, Paloski WH. Sensorimotor posture control in the blind: superior ankle proprioceptive acuity does not compensate for vision loss. Gait Posture 2013;38(4):603—8.
[76] Pau M, Corona F, Leban B, Pau M. Effects of backpack carriage on foot-ground relationship in children during upright stance. Gait Posture 2011;33(2):195—9.
[77] Quek J, Brauer S, Clark R, Treleaven J. New insights into neck-pain-related postural control using measures of signal frequency and complexity in older adults. Gait Posture 2014;39(4):1069—73.
[78] Raymakers J, Samson M, Verhaar H. The assessment of body sway and the choice of the stability parameter(s). Gait Posture 2005;21(1):48—58.
[79] Rigoldi C, Galli M, Mainardi L, Albertini G. Evaluation of posture signal using entropy analysis and fractal dimension in adults with Down syndrome. Comput Methods Biomech Biomed Engin 2012;17(5):474—9.
[80] Robillard R, Prince F, Filipini D, Carrier J. Aging worsens the effects of sleep deprivation on postural control. PLoS One 2011;6(12):e28731.
[81] Sarabon N, Rosker J. Effect of 14 days of bed rest in older adults on parameters of the body sway and on the local ankle function. J Electromyogr Kinesiol 2013;23(6): 1505—11.
[82] Saripalle SK, Paiva GC, Cliett TC, Derakhshani RR, King GW, Lovelace CT. Classification of body movements based on posturographic data. Hum Mov Sci 2014;33:238—50.
[83] Silva AG, Johnson MI. Does forward head posture affect postural control in human healthy volunteers? Gait Posture 2013;38(2):352—3.
[84] Stoffregen TA, Riccio GE. An ecological theory of orientation and the vestibular system. Psychol Rev 1988;95(1):3—14.
[85] Suzuki Y, Nomura T, Casadio M, Morasso P. Intermittent control with ankle, hip, and mixed strategies during quiet standing: a theoretical proposal based on a double inverted pendulum model. J Theor Biol 2012;310:55—79.
[86] Tsai Y-C, Hsieh L-F, Yang S. Age-related changes in posture response under a continuous and unexpected perturbation. J Biomech 2014;47(2):482—90.
[87] van Diest M, Stegenga J, Wörtche HJ, Postema K, Verkerke GJ, Lamoth CJ. Suitability of kinect for measuring whole body movement patterns during exergaming. J Biomech 2014;47(12):2925—32.

[88] Wajda DA, Motl RW, Sosnoff JJ. Correlates of dual task cost of standing balance in individuals with multiple sclerosis. Gait Posture 2014;40(3):352—6.

[89] Wheat JS, Haddad JM, Scaife R. Between-day reliability of time-to-contact measures used to assess postural stability. Gait Posture 2012;35(2):345—7.

[90] Winter D. Human balance and posture control during standing and walking. Gait Posture 1995;3(4):193—214.

[91] Winter DA. Biomechanics and Motor Control of Human Movement. 4th ed; 2009.

[92] Wu G, Cavanagh PR. ISB recommendations for standardization in the reporting of kinematic data. J Biomech 1995;28(10):1257—61.

[93] Wu G, Siegler S, Allard P, Kirtley C, Leardini A, Rosenbaum D, et al. ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion — Part i: ankle, hip, and spine. J Biomech 2002;35(4):543—8.

[94] Wu G, van der Helm FC, Veeger H, Makhsous M, Van Roy P, Anglin C, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion — Part ii: shoulder, elbow, wrist and hand. J Biomech 2005;38(5):981—92.

[95] Yeung L, Cheng KC, Fong C, Lee WC, Tong K-Y. Evaluation of the microsoft kinect as a clinical assessment tool of body sway. Gait Posture 2014;40(4):532—8.

[96] Yu L-J, Stokell R, Treleaven J. The effect of neck torsion on postural stability in subjects with persistent whiplash. Man Ther 2011;16(4):339—43.

[97] Zatsiorsky VM, King DL. An algorithm for determining gravity line location from posturographic recordings. J Biomech 1997;31(2):161—4.