Effects of increased anterior-posterior voluntary sway frequency on mechanical and perceived postural stability

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Abstract

Despite a substantial number of studies, the interaction between mechanical indicators of stability and perception of instability remains unclear. The purpose of this study was to determine the effect of sway frequency and verbal restraint on mechanical and perceived postural stability. Fourteen participants underwent a series of standing voluntary anterior-posterior swaying trials at three frequencies (20, 40, and 60 bpm) and two levels of restraint (non restraint and verbally restraint to swaying at the ankle). Repeated measures ANOVA tests revealed greater mechanical stability defined though the margin of stability, and greater horizontal ground reaction forces, while the centre of pressure excursions remained unchanged with increasing frequency. Furthermore, ground reaction forces were greater in the non-restraint condition. Moreover, a tendency toward greater perceived instability with increasing voluntary sway frequency was observed..Our results indicate that variations in sway frequency and verbal restraint resulted in noticeable alterations in mechanical indicators of stability, with no clear effect on perceived instability.

Keywords: Balance strategies, Inverted pendulum, Extrapolated centre of mass, Biomechanics

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1. Introduction

Subjects with impaired postural control are prone to falls, which are associated with considerable morbidity, suffering from reduced independence, and inability to perform activities of daily living. Research on postural control assessment has focused primarily on the diagnosis of balance disorders and rehabilitation of postural control, as well as understanding the pathophysiology of balance (Visser, Carpenter, Van der Kooij, & Bloem, 2008). However, this sometimes ignores the biomechanical bases of postural stability, which cannot be overlooked when trying to gain a better understanding of postural control.

The biomechanical bases of postural stability have been characterized by a number of variables that are widely used to describe balance in the scientific literature

(Winter, Patla, Ishac, & Gage, 2003). These variables have been studied in relation to the functional base of support (FBoS) which is defined as the maximum excursion of the centre of pressure (CoP) under the feet during a maximal sustained leaning task (King, Judge, & Wolfson, 1994). The dependency of the centre of mass (CoM) control on FBoS has been established through dynamic models, which take into account CoM velocity (Hof, Gazendam, & Sinke, 2005; Pai & Patton, 1997; Riccio, 1993) and even CoM acceleration (Hasson, Van Emmerik, & Caldwell, 2008; Slobounov, Slobounova, & Newell, 1997). These models have demonstrated that when the CoM is outside the FBoS, but is moving towards the FBoS, balance could still be regained. Similarly, when the CoM is inside the FBoS and apparently in a stable state, but is moving outwards, an unstable situation may arise. In order to describe stability under these circumstances, Hof, Gazendam, & Sinke (2005) introduced the “extrapolated CoM” (XCoM) variable, which is based on the position and velocity of the CoM and is indicative of the future position of the CoM if it were to continue moving at that velocity. Therefore, this variable represents the ability to control momentum or the ability to withstand large variability (Granata & England, 2007). From this concept, a margin of stability (MoS) can be defined. The MoS is the distance between the XCoM and the limits of the FBoS in the direction of travel, and therefore represents a mechanical need to make postural adjustments in order to maintain stability (Hof, Gazendam, & Sinke, 2005).

An important assumption in the above is, however, that the body behaves in these circumstances as a one linked inverted pendulum (OLIP). The OLIP model assumes that the body moves as an inverted pendulum with movement limited to the ankle joint. As such, Hasson, Van Emmerik, & Caldwell (2008) confirmed that when the body moves under a physically restricted OLIP a critical MoS indicated a need for an alternative strategy such as stepping. A similar response may have been observed under a voluntary swaying task of increasing frequency (Murnaghan, Elston, Mackey, & Robinovitch, 2009). As the CoM has inertial properties, when frequency is higher, a higher CoM velocity would be expected and therefore it would be more difficult to stop its movement in terms of the control of momentum thus exerting critical MoS. Murnaghan et al. (2009) verbally restricted sway mode to a OLIP, but only CoM displacement and not XCoM was reported. The CoM displacement reduced with increased sway frequency, but it is not clear whether XCoM excursions would have remained constant under the two sway frequencies used, confirming MoS as a mechanical limit. Alternatively, voluntary sway at the higher frequency may have involved a forced change in strategy from a OLIP to a multi linked inverted pendulum (MLIP) (Hof et al., 2005; Ko, Challis, & Newell, 2001). Furthermore, a limit to the maximum frequency where a subject can move as a OLIP has been reported as 1Hz (Murnaghan, Elston, Mackey, & Robinovitch, 2009), and predominately mixed strategies would appear to control the XCoM movement.

Under real life situations, subjects are not restricted to the sole use of a OLIP. On the contrary, it has been reported that subjects use a whole continuum of strategies to control balance, not limited solely to the ankle strategy (Runge, Shupert, Horak, & Zajac, 1999). Slobounov, Slobounova, & Newell (1997) compared a verbally restricted OLIP to a free condition in which subjects were allowed to use a MLIP under voluntary sway and found in both conditions that increased horizontal ground reaction forces (GRF), were evident as the CoP approached the BoS. This would account for a possible change in strategy under critical MoS, yet this was not assessed.

An increased sway frequency may not only lead to a shift towards MLIP movement strategies, but also to an altered perception of stability and therefore potentially less XCoM motion than what would be mechanically possible (Murnaghan, Elston, Mackey, & Robinovitch, 2009). Under quiet bipedal standing, increased postural threat such as an increased height of the support surface has been shown to lead to maintaining a greater MoS (Hauck, Carpenter, & Frank, 2008; Huffman, Horslen, Carpenter, & Adkin, 2009); which may be identified as a protective strategy as subjects become more conscious of their posture with greater perceived instability (Huffman et al., 2009). One would expect also with increased voluntary sway frequency that perceived instability increases, yet to the authors' knowledge this has not yet been investigated as such.

The purpose of this study was to determine the effect of sway frequency on mechanical and perceived stability under a) unrestricted voluntary anterior-posterior sway and b) when verbally restricted to OLIP. We hypothesised that with increasing sway frequencies the MoS would increase and perception of instability would be greater thus limiting mechanically possible performance. A potential change in strategy from OLIP to MLIP will be taken into consideration, as this was expected to jeopardise a strict interpretation of MoS as an indicator of stability.

2. Methods

2.1. Participants

Fourteen healthy subjects, 5 male and 9 female, participated in this study. Median (range) of their age was 25 years (21-50), height 167.4 cm (158.4-188), and weight 65 kg (56-100). Inclusion criteria for this study were the absence of chronic or musculoskeletal injuries within the previous 3 months or diagnosed sensory impairments (Stolze et al., 2004) and an age within the range of 18 and 60. Subjects read and signed a consent form prior to testing. This study received full ethical approval from the Research Ethics Committee of Liverpool John Moores University.

2.2. Protocol

Each participant performed a total of six experimental conditions defined by the combination of anterior/posterior swaying frequencies and task restraint. Swaying frequencies were randomized and selected according to previous studies as 20 bpm (0.33 Hz), 40 bpm (0.66 Hz) and 60 bpm (1.00 Hz) (Murnaghan, Elston, Mackey, & Robinovitch, 2009). Desired oscillation frequency was defined by acoustic cues given by an electronic metronome (Web Metronome, 2006). The participant was asked to sway completing half a cycle between successive beats, which determined that the participant would have reached a maximal forward lean at one beat followed by a maximal backward lean at the next beat. Participants performed the three frequency conditions under two different task restraints: a no restraint (NR) condition in which they were instructed to sway freely back and forth as far as possible in any manner they wished (no visual demonstration given); and a restraint (R) condition in which they were instructed to sway back and forth as far as possible with movement limited by verbal instruction to rotation at the ankles (Slobounov, Slobounova, & Newell, 1997). The NR conditions were performed first to prevent a carryover effect of restrained swaying technique into the NR condition. A minimum of one-minute rest between trials was given to avoid fatigue effects.

Throughout the trials, foot position was standardized with participants barefoot. Each foot was externally rotated by ± 15º angle and the heels were separated 5 cm left and right of the sagittal plane (Kirby, Price, & MacLeod, 1987). A visual guide was placed on the floor to ensure that the feet were kept in the same position throughout the trials (Figure 1). Subjects were asked to remain relaxed, with the arms hanging parallel to the trunk, and for the duration of the trials to look straight ahead at a spot placed at eye level at a distance of 5 metres.

In order to record the FBoS each participant performed a maximal sustained leaning task. The participant was asked to slowly lean forward as far as possible, in the standardised position described earlier, through movement at the ankles, and backwards in the same manner to reach the maximal sustained lean for three seconds (Forth, Fiedler, & Paloski, 2011; Gouglidis, Nikodelis, Hatzitaki, & Amiridis, 2011; King, Judge, & Wolfson, 1994). This task was repeated three consecutive times and peak CoP in the anterior-posterior direction during the three-second sustained leaning position was used to define the FBoS.

Following the FBoS recording, subjects were asked to perform the required tasks according to the six experimental conditions (NR and R at three frequencies each). The instruction to try to reach the maximum amplitude in each oscillation as well as the instruction to recover balance if needed was given to ensure maximal performance. If participants took a step or were unable to attain the frequency requirements that trial was discarded and repeated. However, this was not necessary as no subject took a step and all were able to comply with the frequency requirements. An approximately 10 s familiarization prior to the recording of each trial was given and when subjects indicated verbally that they were ready to begin, recording began. Participants' performance was recorded for 20 seconds.

2.3. Data Collection

A motion capture system (Qualisys Motion Capture System, Gothenburg, Sweden) and a 90 x 60 cm force platform (Kistler Instrument Corp., Amherst, U.S.A.) were used to record kinematic and force data at 250 Hz. Seventy two reflective markers were placed on anatomic landmarks to define the head, thorax, upper arms, lower arms, pelvis, upper legs, lower legs, and feet segments according to a full body 6 degree of freedom segmental model (Besier, Sturnieks, Alderson, & Lloyd, 2003). Perceived instability was measured immediately after each trial using a visual analogue scale in which the participants were asked to draw a mark on a 100 mm line, between 0 mm (maximum stability perception) and 100 mm (minimum stability perception). This was based on the subjective stability scoring system designed by

Schieppati, Tacchini, Nardone, Tarantola, & Corna (1999) and has shown to be valid and reliable for balance tasks such as quiet stance, single leg stance, and reaching tasks for healthy young adults (Hauck, Carpenter, & Frank, 2008).

2.4. Data Analysis

Data was analysed using Visual3D software (C Motion Inc., Germantown, U.S.A.). Marker positions were smoothed using a zero-phase fourth-order Butterworth low-pass filter with a cut-off frequency of 20 Hz, while force data was filtered using a Critically Damped low pass filter also with a cut off frequency of 20 Hz. Dependent variables were 1) minimum margin of stability (MoS) (m) according to (Hof, Gazendam, & Sinke, 2005); 2) peak CoP displacement (m); 3) peak horizontal GRF normalized to body mass (N·kg-1); 4) ankle and hip angles (degrees); and 5) perceived instability (mm). Anterior and posterior swaying values for variables were analysed separately. Peak values were obtained from the single largest anterior or posterior value for each trial, representing maximal performance. MoS (FBoS - XCoM) when positive indicated that the furthest displacement of XCoM remained within the FBoS, both for anterior and posterior values, whereas when negative indicated that the furthest displacement of the XCoM was outside the FBoS. Therefore, a reduced negative MoS or an increased positive MoS should be interpreted as greater mechanical stability. Peak horizontal GRF and peak CoP displacement were expressed in the lab coordinate system, positive in anterior and negative in posterior direction. For the purpose of adequate interpretations, anterior XCoM displacement is expected to be countered with anterior COP displacement and/or posterior GRF (see Hof et al., 2005). Figure 2 provides an example of XCoM, FBoS and CoP relationship across frequencies and conditions for one subject.

2.5. Statistical Analysis

Descriptive and inferential statistics were obtained through the IBM® Statistical Package for the Social Sciences (SPSS, version 19.0). A one-sample Kolmogorov-Smirnov test was applied to the data to ensure a normal distribution. Accordingly, and in order to determine the main and interaction effects of the six experimental conditions on minimum XCoM, MoS, peak CoP, peak horizontal GRF, and perceived instability, repeated measures ANOVA tests were used with two within subject factors: restraint (NR, R) and frequency (20, 40, 60). Post hoc analyses were conducted for significant interactions between restraint and frequency with a Bonferroni adjustment for multiple comparisons. Significance level was set at $p<0.05$. Mean and Standard Deviation (□SD) values will be presented.

3.0 Results

MoS varied significantly with frequency in both anterior ($F_{1.43, 18.54} = 9.059$, $P=0.004$) (see Figure 3a) and posterior ($F_{1.33, 17.27} = 5.932$, $P=0.019$) (see Figure 3b) directions, but neither the frequency-restraint interaction in the anterior ($F_{2,26} = 0.8621$, $P=0.434$) or posterior ($F_{2,26} = 0.171$, $P=0.844$) directions, nor the main effect of restraint in the anterior ($F_{1,3} = 1.270$, $P=0.282$) or posterior ($F_{1,13} = 0.422$, $P=0.527$) directions were significant. Regarding the frequency main effect, a reduced negative MoS was found in the anterior direction from 20 to 60 bpm ($p<0.05$) and from 40 to 60 bpm ($p<0.001$); and an increased MoS was found in the posterior direction from 20 to 60 bpm ($p<0.05$).

Regarding the COP (Figure 4), there was no frequency main effect in the anterior ($F_{1.5,16.22} = 0.051$, $P=0.873$) or posterior ($F_{1.13,14.79} = 1.956$, $P=0.183$) directions, and no restraint main effect in the anterior ($F_{1,13} = 0.544$, $P=0.474$) or posterior ($F_{1,13} = 0.661$, $P=0.431$) directions. In addition, no frequency-restraint interaction effect on peak COP was found in both anterior

($F_{2,26}$ = 1.064, P=0.360) and posterior ($F_{2,26}$ = 1.092, P=0.351) directions (See Figure 3 for an example on one subject). However, results show a frequency main effect on GRF peak values in both posterior ($F_{1.34,\ 17.47}$ = 43.675, P=0.000) (see Figure 5a) and anterior ($F_{1.48,\ 19.28}$ = 39.303, P=0.000) (see Figure 5b) directions. Post hoc analysis revealed an increase in GRF in the posterior direction with increasing frequency from 20 to 40 bpm ($p<0.001$), from 20 to 60 bpm ($p<0.001$), and from 40 to 60 bpm ($p<0.01$). Similarly, in the anterior direction, an increase in GRF with increasing frequency was observed from 20 to 40 bpm ($p<0.001$), from 20 to 60 bpm ($p<0.001$), and from 40 to 60 bpm ($p<0.01$). Furthermore, a significant main effect was found for restraint on GRF where GRFs were significantly higher in the NR condition compared to the R condition for anterior ($F_{1,13}$ = 12.463, P=0.004) and posterior ($F_{1,13}$ = 8.408, P=0.012) directions. Moreover, ankle-hip angle-angle plots, plotted from the sample average, showed qualitatively a greater hip contribution with increasing sway frequency, and this more so in the NR condition than in the R condition (Figure 6). Whilst the angle-angle plots can reveal changes in joint coordination, counter rotations of segments (MLIP mechanism) are associated with accelerating the trunk segment to generate so-called counter rotation of the lower limb segments (retention of total body angular momentum) which in turn leads to the generation of horizontal forces. Therefore, changes in strategy based on angle-angle plots are only indirect observations. No frequency-restraint interaction effect was found for GRF in both anterior ($F_{1.4,18.2}$ = 2.329, P=0.137) and posterior ($F_{2,26}$ = 0.837, P=0.444) directions.

Regarding perceived instability, restraint had no effect on this variable ($F_{1,13}$ = 1.474, P=0.246). In addition, no frequency-restraint interaction effect was found ($F_{2,26}$ = 0.205, P=0.816). However, perceived instability showed a tendency to increase with increasing frequency from the lowest to the highest frequency independently of restraint ($F_{2,26}$ = 3.131, P=0.06). This means that subjects showed a tendency to feel more unstable at the highest frequency (Figure 7).

4.0 Discussion

The purpose of this study was to determine the effect of sway frequency on mechanical and perceived stability under an unrestricted voluntary anterior-posterior sway and when verbally restricted to OLIP. Results showed an increased MoS with increasing frequency in the posterior direction, and a reduced negative MoS in the anterior direction. Peak values of MoS were always negative for the anterior direction meaning that the XCoM was allowed to move outside the FBoS. On the other hand, MoS for the posterior direction was positive meaning that the XCoM was kept safely inside the FBoS. In addition, horizontal GRF peak values increased with increasing frequency and were greater for the NR condition in both the anterior and posterior directions while peak COP remained unchanged throughout conditions. A tendency for perceived instability to increase with increased frequency was observed, yet this remains to be confirmed in future research.

We found an increased MoS with increasing frequency in the posterior direction and a reduced negative MoS in the anterior direction, which is in contrast to some earlier studies in which MoS has been shown to decrease with increasing task difficulty (Hasson, Van Emmerik, & Caldwell, 2008; Hof, Gazendam, & Sinke, 2005). Unlike the present study, Hof, Gazendam, & Sinke (2005) used a static task with increasing difficulty by reducing the base of support. Hasson, Van Emmerik, & Caldwell (2008) used a similar task in which subjects physically restricted to a OLIP were told to resist perturbations of increasing intensity and resume quiet stance as quickly as possible, only stepping when necessary. Unlike the present study, their results demonstrated a strong inverse linear relationship of MoS with postural challenge level. According to these studies, MoS would ultimately reach a zero or negative value with further increasing difficulty, indicating that the XCoM goes outside the FBoS and a change in strategy is necessary (Hof, Gazendam, & Sinke, 2005). Similarly, Hasson, Van

Emmerik, & Caldwell (2008) observed a change to a stepping strategy when the MoS was zero or negative. However, subjects were physically restricted to a OLIP and only stepping was possible. Conversely, in the present study, subjects were not physically restricted to a OLIP, and MoS increased with increasing sway frequency in the posterior direction and the negative MoS was reduced in the anterior direction. Furthermore, MoS peak values in the anterior direction were always negative, yet no trials involving steps were reported in our study. Considering that counter rotation of segments was available as alternative strategy prior to stepping (Hof, Gazendam, & Sinke, 2005; Hof, 2007), increased hip contribution was observed with increasing frequency. However, this was not statistically tested, and comparisons should be made with caution as the nature of the tasks differed considerably.

Counter rotation of segments can be indirectly quantified through the occurrence of horizontal GRFs (Hwang et al., 2009; Slobounov et al., 1997; Tijtgat et al., 2012). We observed increasing horizontal GRF peak values with increasing frequency, hence suggesting an increasing involvement of MLIP strategies. Where horizontal GRFs were greater for the non-restricted sway in both the anterior and posterior directions, swaying restricted verbally to OLIP still appeared to involve primarily adaptation of MLIP mechanisms with increased sway frequency. Furthermore, ankle-hip angle-angle plots showed a greater hip contribution with increasing sway frequency, and this more so in the NR condition than in the R condition (Figure 6). Considering perception of instability and postural strategy as confounding factors in the relationship between frequency and mechanical stability, further studies should address a possible change in strategy as an adaptation to an increase in perceived instability with increased frequency.

Similarly, increased horizontal GRFs with increased perturbation speed have been reported previously (Hwang et al., 2009). The present study did show that COP remained unchanged throughout all conditions; thus, MLIP mechanisms, indirectly assessed through increasing horizontal GRFs, might appear when conscious alterations of sway frequency determine increased difficulty, whilst the contribution of the ankle strategy to the task was the same for all conditions.

As stated earlier, and contrary to some existing scientific literature (Hasson, Van Emmerik, & Caldwell, 2008), MoS increased with increasing task difficulty in the posterior direction and negative MoS was reduced in the anterior direction. Besides the above explanations based on mechanical differences between tasks, the different nature of the tasks might also account for this discrepancy, with the task in the present study being more conscious and others having been more reactive. Previous studies have reported that greater perceived instability leads to the use of a more protective strategy thus limiting the use of mechanical stability limits (Hauck, Carpenter, & Frank, 2008; Huffman, Horslen, Carpenter, & Adkin, 2009). Accordingly, the present study observed a non-significant tendency towards greater perceived instability with increasing sway frequency. Considering the conscious nature of the task, it is possible that the greater perceived instability led to the increased MoS values with increasing sway frequency.

This interpretation would be in line with new approaches to the understanding of postural control based on the ability to withstand variability during a postural control task (Granata & England, 2007). Accordingly, a change in strategy would allow subjects to withstand large variability defined by the position of the XCoM outside the FBoS and would allow to reduce this variability under an increasing sway frequency related to a subjective perception of stability such as fear of falling (Granata & England, 2007).

There are several limitations to the present study, which should be taken into account. The MoS was positive in the posterior direction, unlike the anterior direction, suggesting a limited exploitation of the OLIP mechanism to maintain balance. Anterior GRFs observed with XCoM motion in the posterior direction suggest the use of a MLIP strategy even when unnecessary which might be related to differences in perceived instability between directions, which were not assessed, yet anecdotally reported by our participants to be greater in the posterior direction. Future studies could assess direction specific perceived instability to ascertain this issue. It is possible that a MLIP was present throughout conditions as assessed through horizontal GRFs and hip contribution to sway, even in the R condition which verbally restrained subjects to the OLIP. However, this was not statistically tested for and should therefore be the object of future studies. Evaluating the contributions of individual segmental counter rotation to the MLIP strategy, for example due to knee or hip torques, trunk flexion/extension, or arm movements, was beyond the scope of this study and could be assessed in future studies to for example help identify neuromuscular control deficits in certain patient populations. Finally, perception of instability and strategy as confounding factors in the relationship between frequency and mechanical stability was suggested, therefore further studies should address a possible change in strategy as an adaptation to an increase in perceived instability with increased frequency.

5.0 Conclusion

We hypothesised that with increasing sway frequency the MoS would increase, seemingly limiting mechanically determined performance due to employing alternative MLIP strategies as well as increased perceived instability. Our results suggest a possible change in postural strategy indirectly assessed through an increased hip contribution and horizontal GRFs with increasing frequency, which led to an increased MoS in the posterior direction and a reduced negative MoS in the anterior direction despite increased task difficulty. Around the FBoS a wider area can be delimited in which balance can be maintained when using a MLIP, however, the experimental conditions provided no conclusive evidence towards increased perceived instability with increasing frequency.

6.0 Appendices

Descriptive statistics for frequency and restraint conditions in both anterior and posterior directions

7.0 Conflict of interest

There was no conflict of interest.

8.0 Acknowledgements

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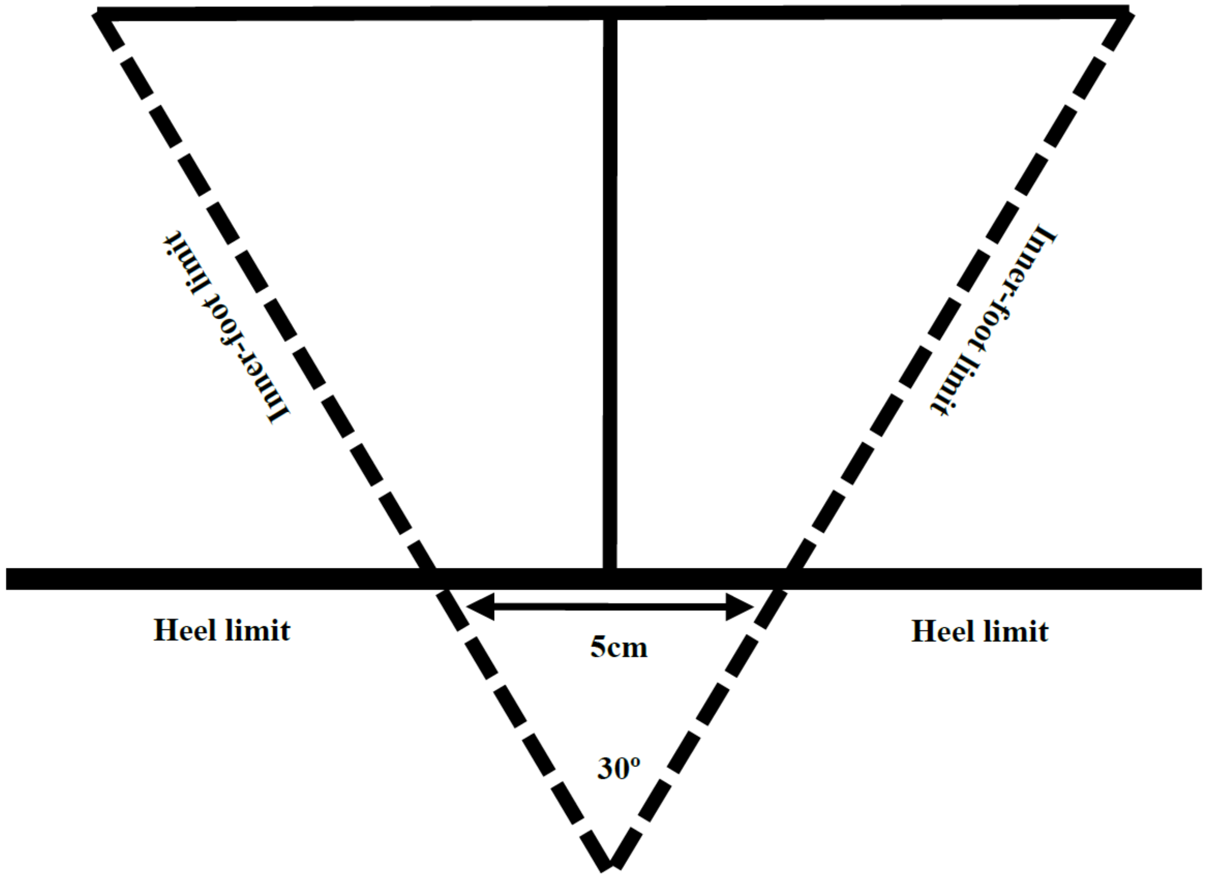

Figure 1. Template for standardized position of the feet on the force platform.

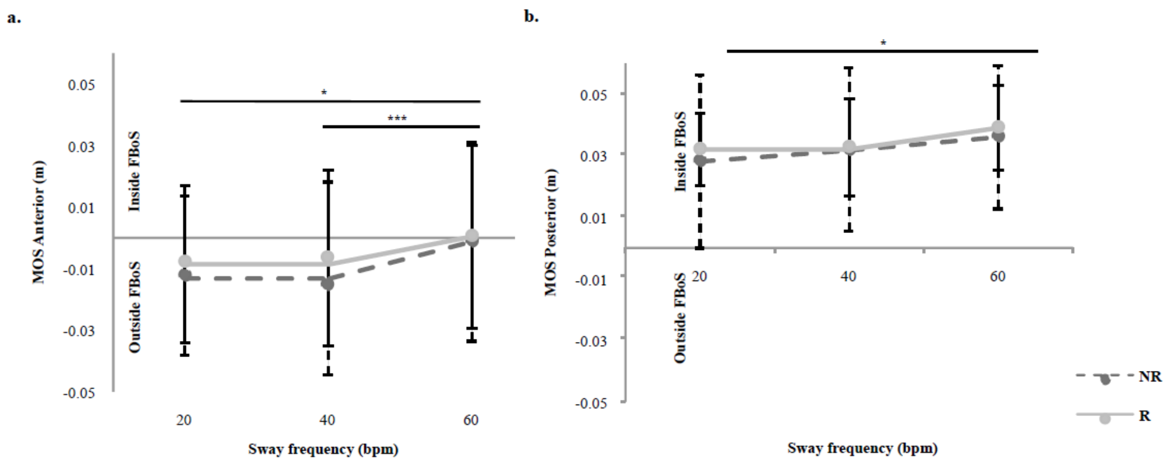

Figure 2. Plots for one example participant of the extrapolated centre of mass (grey) and centre of pressure (black) displacement with respect to the anterior and posterior functional base of support (FBoS) for the restricted condition at 20 (a), 40 (b) and 60 (c) beats per minute and the non-restricted condition at 20 (d), 40 (e) and 60 (f) beats per minute.

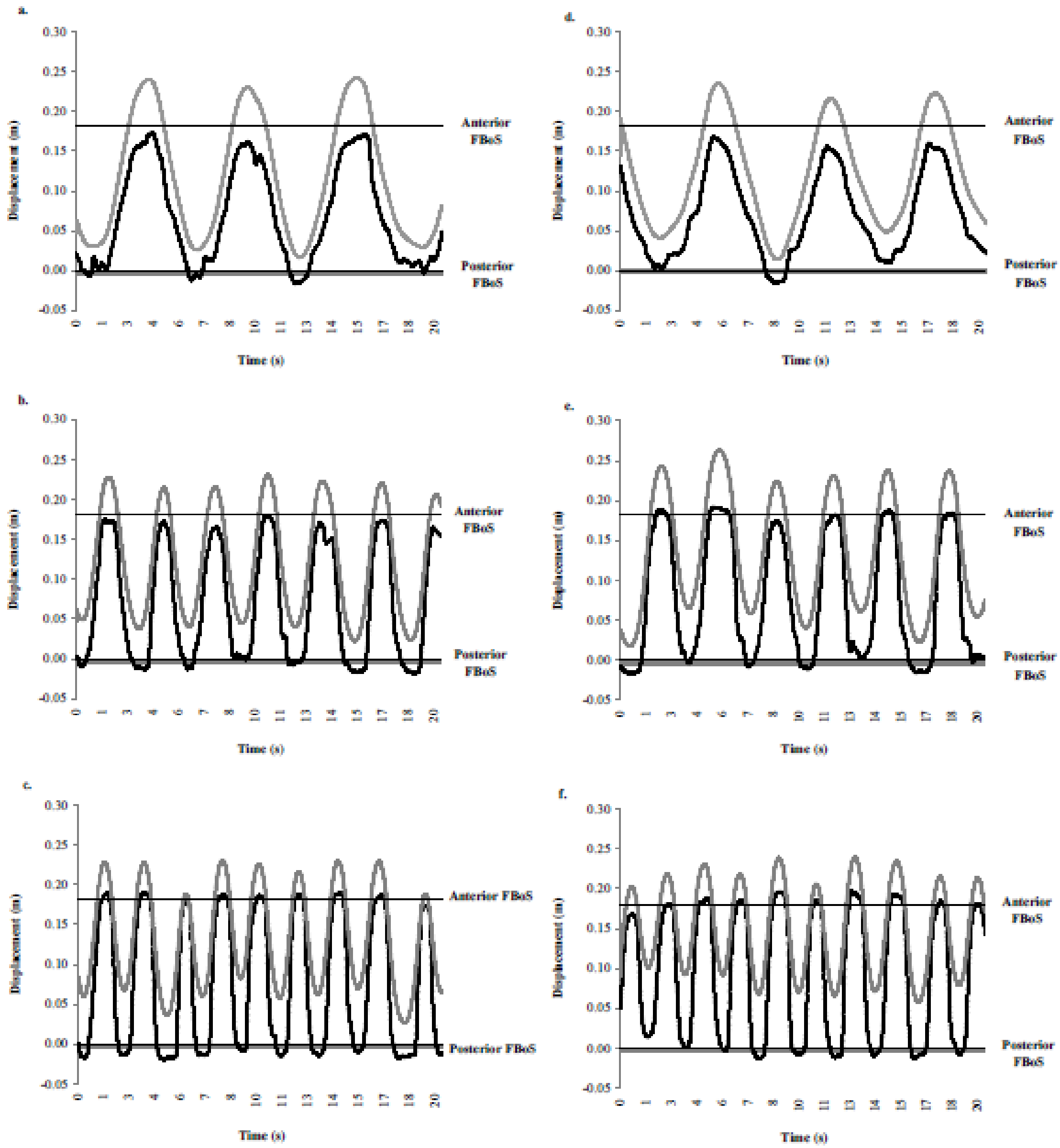

Figure 3. Effect of experimental conditions on anterior (a) and posterior (b) minimum margin of stability (MoS) (Mean±SE) in non-restricted (NR) and restricted (R) sway. * ($p<0.05$); *** ($p<0.001$) indicate significant differences between frequencies.

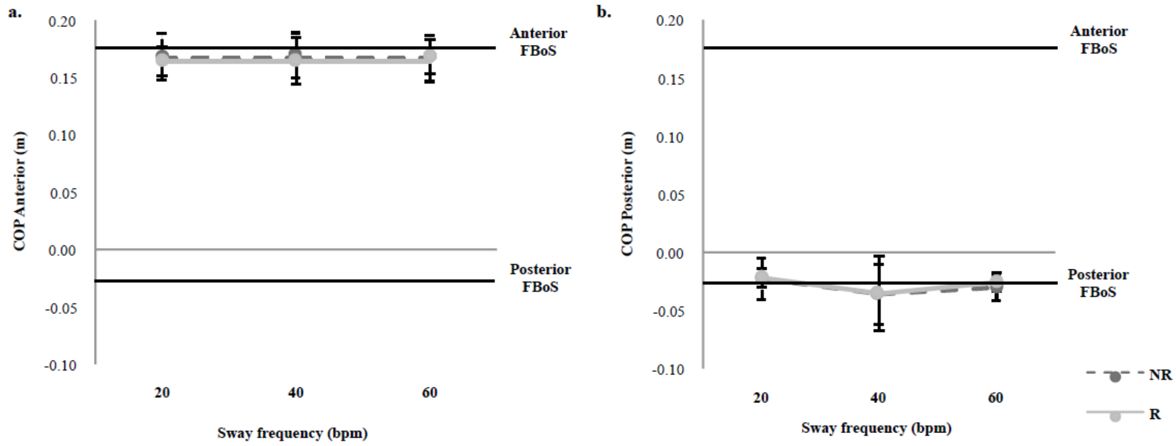

Figure 4. Effect of experimental conditions on anterior (a) and posterior (b) peak centre of pressure displacement (CoP) (Mean±SE) in non-restricted (NR) and restricted (R) sway.

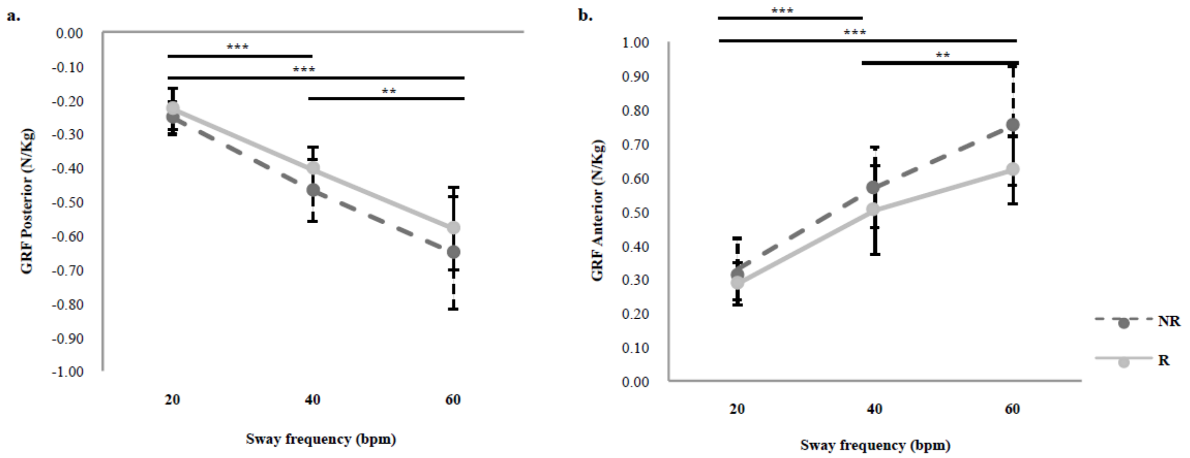

Figure 5. Effect of experimental conditions on anterior (b) and posterior (a) ground reaction forces (GRF) (Mean±SE) in non-restricted (NR) and restricted (R) sway. ** ($p<0.01$); *** ($p<0.001$) indicate significant differences between frequencies. Posterior is shown on the left, contrary to figures 2 and 3, as it relates to anterior correction of postural stability.

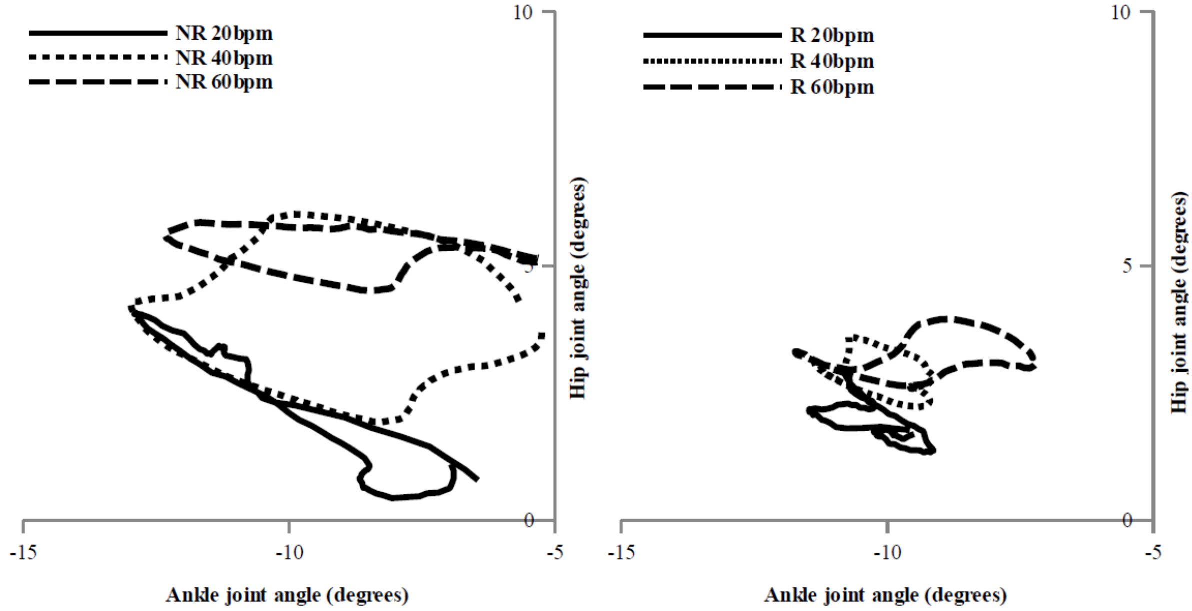

Figure 6. Ankle-hip angle-angle plots, plotted from the sample average, for non-restricted (NR) and restricted (R) sway for each sway frequency in beats per minute (bpm).

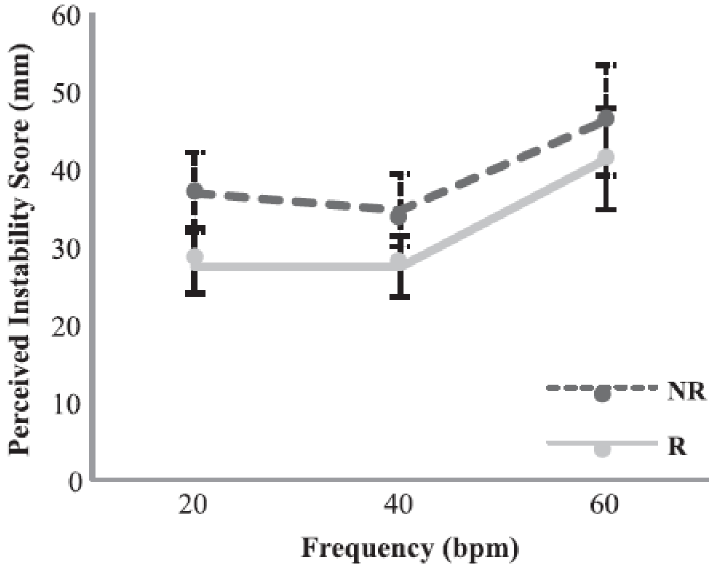

Figure 7. Effect of experimental conditions on perceived instability assessed by means of a visual analogue scale (VAS) (Mean±SE) in non-restricted (NR) and restricted (R) sway.