



Communication

A kinematics recommendation for trunk stability and control assessments during unstable sitting

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ABSTRACT

Trunk control has been commonly studied via an unstable sitting paradigm, with the majority of analyses using angular kinematics-based, posturographic measures. However, considerable variability in the choice of kinematics exists. Furthermore, the kinematics capturing the completion of this task are unknown. The purpose of this study was to characterize the kinematics in unstable sitting by quantifying and comparing the angular motion of the base of support, pelvis, and trunk as elicited via a commonly used wobble board (WB) paradigm. WB, pelvis, and trunk motion was recorded in fifteen non-disabled participants sitting on a wobble board. Posturographic measures were calculated and compared between corresponding WB and pelvis, and between WB and trunk angles. The trunk was stabilized through relatively large WB motion, with the trunk adopting a quasi-static pose. For all measures, angles, and conditions, the WB measure values were significantly larger than their corresponding pelvis or trunk values. Our findings demonstrate that the WB-human system is stabilized by regulating WB motion. Future work utilizing an unstable sitting surface and kinematics-based analyses to investigate trunk control should include the analysis of base of support kinematics.

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1. Introduction

Considering that trunk stability is of general importance in human balance control and mobility, it comes as no surprise that it is critical for maintaining stability of the body during sitting [1]. Trunk stability and its control have been commonly studied via an unstable sitting paradigm, where an unstable surface serves as the base of support (BoS). Using, for example, a wobble board, such studies have investigated: differences in trunk control between different populations [2–8]; the effect of applied trunk forces [9], whole body vibration [10], or sensory manipulation [11] on trunk control; and methodological choices, e.g., task difficulty and kinematic outcome measures, that can optimize trunk control assessments and their reliability [11–15].

While the majority of analyses have focused on the use of angular kinematics-based, posturographic measures, considerable

variability in the choice of kinematics exists. Kinematics used include those of the: BoS [6,7,9,10,12–14]; pelvis [4,6,15]; pelvis relative to the BoS [7]; lumbar spine relative to the BoS [5]; lumbar spine relative to the pelvis [7]; thoracic spine [6,11,15]; thoracic spine relative to the pelvis [4,6,8,15]; thoracic spine relative to the lumbar spine [2,3]; and thoracolumbar spine relative to the BoS [12]. This comes as no surprise as no study to date has actually investigated the kinematics capturing task completion in unstable sitting. An understanding of the kinematics important for assessing trunk control during unstable sitting could be valuable for recommending the kinematics to be measured in future research and assessments pertaining to unstable sitting.

The purpose of this study was therefore to characterize the kinematics in unstable sitting by quantifying and comparing the angular motion of the base of support, pelvis, and trunk as elicited via a wobble board paradigm. Based on a biomechanical assessment of unstable sitting, we hypothesized that the task is completed by adopting a quasi-static pose of the upper body while regulating the motion of the base of support.

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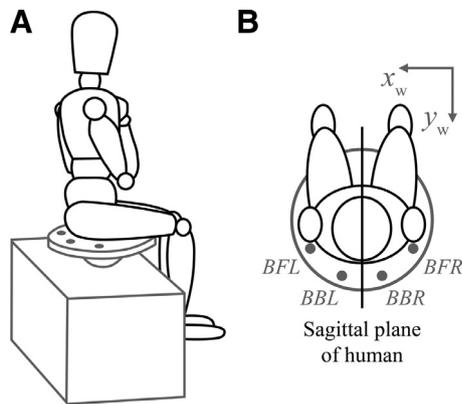


Fig. 1. Schematic of wobble board balancing (A); and aerial view of wobble board-human system (B), with the following markers attached: board front left (BFL), board back left (BBL), board back right (BBR), and board front right (BFR). In (B), the orientation of the local coordinate system of the wobble board relative to the sagittal plane of the participant is shown. Specifically, the y_w axis of the wobble board (y_w) was aligned with the sagittal plane of the participant.

2. Methods

2.1. Participants and experimental procedures

Fifteen non-disabled, young and male individuals were invited to participate in this study (age 25 ± 5.2 years; height 179.6 ± 6.7 cm; and weight 75.1 ± 13.0 kg; mean \pm standard deviation). All participants reported no history of neurological or musculoskeletal impairments or pain, gait or balance difficulties, or use of a walking aid. All participants gave written informed consent to the experimental procedures, which were approved by the Health Research Ethics Board of the University of Alberta (Study ID: Pro00039437).

Participants were asked to sit on a custom-made wobble board (Fig. 1(A)) with their sagittal plane aligned with the anterior-posterior axis of the wobble board as defined via four motion capture markers (Fig. 1(B)). The wobble board, which is described elsewhere [16], was used to induce unstable sitting as elicited by its challenging postural environment. Hemispherical bases of different radii of curvature could be attached to the bottom of the sitting surface to allow for different levels of instability. For each participant, four 35 s trials were performed for each of two task conditions: (1) an easier base and eyes closed (B1EC; radius of curvature: 20 cm); and (2) a more difficult base and eyes open (B2EO; radius of curvature: 13 cm). We specifically included two task conditions to improve the validity of our findings, not to compare kinematics across task conditions. Each task condition had a different base and eye condition as modifying task difficulty is common in studies focused on kinematics-based analyses and unstable sitting paradigms [3,4,6,9–14]. To reduce potential learning effects, each participant performed one 60 s practice trial for each task condition. A resting break of 30 s was given in between trials.

Kinematic data of the wobble board, pelvis, and thoracic spine (hereafter referred to as *trunk*) were recorded at a sampling rate of 100 Hz using an eight-camera motion capture system (Eagle Digital Camera, Motion Analysis, Santa Rosa, California, USA). In addition to the four markers placed on the wobble board (Fig. 1(B)), four markers were placed on the following pelvis landmarks [17]: bilaterally on the anterior superior iliac spine and posterior superior iliac spine. Four markers were also placed on the following trunk landmarks [18]: the seventh cervical vertebra, the eighth thoracic vertebra, the deepest point of the incisura jugularis, and the processus xiphoideus. For subsequent analyses, a 30 s segment [13], starting 1 s into each trial, was isolated in each trial's motion data.

Missing motion capture markers of four or less consecutive frames [19] were recreated using spline interpolation [20]. Following interpolation, trials still affected by missing data were removed from subsequent analyses.

2.2. Experimental data processing and analysis

To obtain the kinematics of the wobble board, pelvis, and trunk for each trial (all relative to the global coordinate system (GCS)), the coordinate systems of the wobble board (WCS), pelvis (PCS) [17], and trunk (TCS) [18] were defined using the raw marker data. The rotation matrices from GCS to WCS, R_w , from GCS to PCS, R_p , and from GCS to TCS, R_t , were identified according to [21]. The three-dimensional angles of the wobble board, pelvis, and trunk were extracted from R_w , R_p , and R_t , respectively, using a Cardan rotation sequence: flexion/extension (F/E) – lateral bending (LB) – axial rotation (Rot) about the moving axes of WCS, PCS, and TCS, respectively, according to [22]. Only F/E and LB were used in subsequent analyses as the wobble board does not induce substantial perturbations in the axial rotation direction. The obtained kinematic time series were first filtered using a zero phase-shift, fourth-order low-pass Butterworth filter with a cut-off frequency of 2.5 Hz [3], and then demeaned.

To quantify and compare the motion of the wobble board, pelvis, and trunk during the balancing task, three posturographic time-domain measures were calculated for each kinematic time series: the range of the angle (RANGE), root mean square of the angle (RMS), and mean of the absolute angular velocity (MVELO) [23]. These measures, which capture the range, variance, and mean speed of an angle, respectively, were chosen as they are commonly used in kinematics-based analyses and unstable sitting paradigms when investigating trunk stability and its control [2,3,6,7,9–15]. A two-tailed, paired t -test was used to assess, for a given measure and condition, whether significant differences exist between corresponding wobble board and pelvis kinematics (e.g., wobble board F/E and pelvis F/E) and corresponding wobble board and trunk kinematics (e.g., wobble board LB and trunk LB). We applied Bonferroni corrections in all our comparisons and used a statistical significance level of $\alpha = 0.05$. All dependent variables obeyed a normal distribution, as tested by a Kolmogorov–Smirnov test [24]. Details on the experimental data analysis are provided in *Supplement S1*.

3. Results

In Fig. 2, representative examples of F/E versus LB for wobble board, pelvis, and trunk kinematics for the B1EC (A, B, and C) and B2EO conditions (D, E, and F) are shown for a single participant. A visual inspection suggests that the pelvis and trunk remained relatively stationary, whereas wobble board F/E and LB were comparably variable during the balancing task.

In Fig. 3, group RANGE, RMS, and MVELO values (mean and one standard deviation) for wobble board, pelvis, and trunk F/E and LB under B1EC and B2EO conditions are shown. For all measures, angles, and conditions, the wobble board values were significantly larger than their corresponding pelvis or trunk values (Fig. 3), with the two-tailed, paired t -test revealing statistically significant differences in all 24 comparisons ($p < 1 \times 10^{-2}$). Comparisons with p less than 1×10^{-2} , 1×10^{-4} , or 1×10^{-6} are marked with one, two, or three asterisks, respectively (Fig. 3). The RANGE and RMS results verify the visual inspection of Fig. 2 where the pelvis and trunk remained relatively stationary and displaced significantly less than the wobble board during balancing. The MVELO results suggest that the pelvis and trunk displaced significantly slower than the wobble board during balancing. Posturographic measure and p values are tabulated in *Supplement S2*.

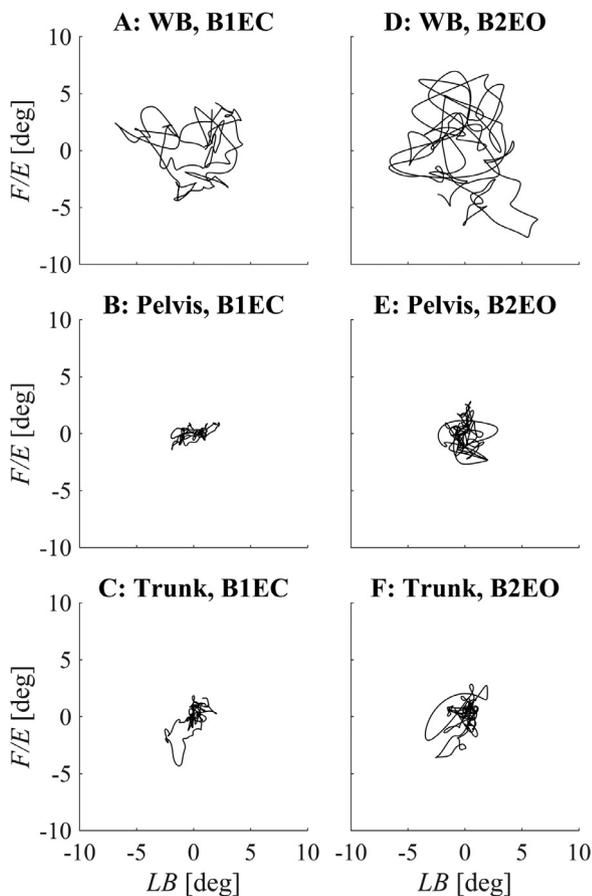


Fig. 2. Representative examples of flexion/extension (F/E) versus lateral bending (LB) for wobble board (WB), pelvis, and trunk kinematics for a single participant. (A), (B), and (C): planar phase plots for the Base 1 Eyes Closed condition (B1EC); (D), (E), and (F): planar phase plots for the Base 2 Eyes Open condition (B2EO).

4. Discussion

The purpose of this study was to obtain an understanding of the kinematics characterizing task completion in unstable sitting. Our results show that, during unstable sitting, the trunk is stabilized through relatively large, fast displacements of the BoS, whereas both the pelvis and trunk remain relatively upright and stationary.

4.1. Biomechanical insights and practical recommendations

The primary goal of the wobble board-human dynamic system is to stabilize the upper body. Mechanically, the wobble board was lighter, smaller, and of lower inertia compared to the upper body. Therefore, it is reasonable to assume the system is most effectively stabilized by regulating the motion of the wobble board. While this biomechanical assessment agrees with our findings, future work could investigate how the central nervous system uses sensory feedback and previous experience to decide that adopting a quasi-static pose of the upper body while regulating the motion of the base of support may be the best stabilization strategy.

In studies that have utilized an unstable sitting surface to investigate or assess trunk stability and its control, considerable variability in the choice of kinematics exists [2–15]. However, no study to date has investigated the kinematics characterizing task completion in unstable sitting. The finding that the task is characterized by and completed through relatively large motion of the BoS and relatively small motion of the upper body allows us to isolate the most sensitive kinematic measures in unstable sitting. We

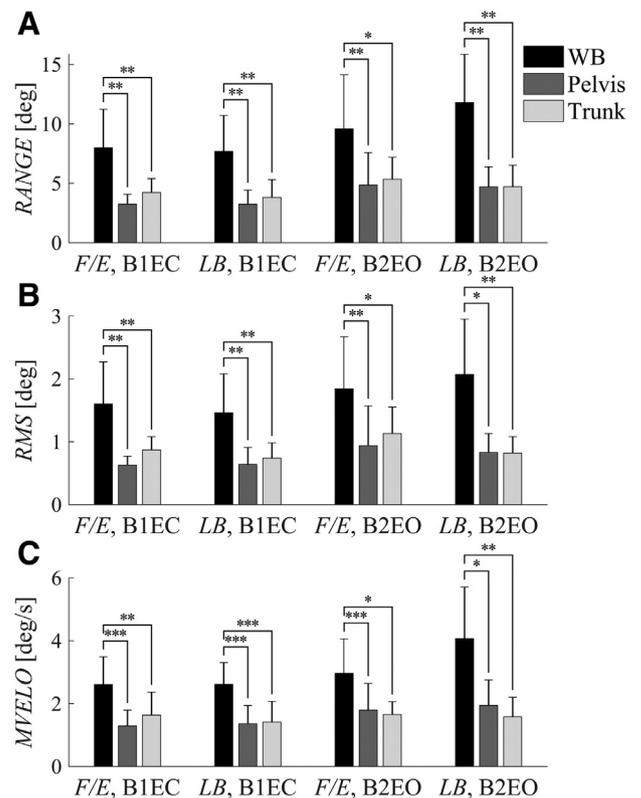


Fig. 3. Posturographic time-domain measures for wobble board (WB), pelvis, and trunk kinematics. Shown are the range of the angle ($RANGE$) (A), root mean square of the angle (RMS) (B), and the mean of the absolute angular velocity ($MVELO$) (C) for flexion/extension (F/E) and lateral bending (LB) under the Base 1 Eyes Closed (B1EC) and Base 2 Eyes Open (B2EO) conditions. All values are presented as mean and one standard deviation (presented variability is *inter-participant*). A two-tailed, paired t -test revealed statistically significant differences between WB and pelvis kinematics and between WB and trunk kinematics for all measures, angles, and task conditions ($p < 1 \times 10^{-2}$; 24 comparisons). Comparisons with p less than 1×10^{-2} , 1×10^{-4} , or 1×10^{-6} are marked with one, two, or three asterisks, respectively.

therefore propose that future research and assessments utilizing kinematics-based analyses of unstable sitting be standardized by including some variation of BoS kinematics.

4.2. Limitations

Since all study participants were male, we were unable to investigate potential sex differences in the unstable sitting kinematics. However, based on previous work [6,7], it can be hypothesized that similar results hold true for females. Nonetheless, future work should examine whether our findings do apply to other populations.

This study used a hemispherical base attached to the bottom of the sitting surface to induce unstable sitting. However, several types of sitting surface bases have been used in studies investigating trunk control, including: a central ball bearing [5,7]; a central ball-and-socket and spring [6,9,10,12–14]; and hemispherical [2–4,8,11,15] bases. These unstable sitting paradigms are all mechanically similar, with the base of support in each case able to displace freely about a central pivot. We therefore expect that our findings apply to other types of unstable sitting paradigms.

4.3. Conclusions

During unstable sitting, the trunk is stabilized through relatively large, fast displacements of the BoS, whereas the trunk adopts a quasi-static pose. We recommend that future studies

utilizing an unstable sitting surface and kinematics-based analyses to investigate or assess trunk control should include analyses involving some variation of the BoS kinematics (i.e., BoS relative to global or trunk relative to BoS).

Declaration of Competing Interest

None declared.

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Ethical approval

The study was approved by the University of Alberta Health Research Ethics Board (Study ID: Pro00039437).

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.medengphy.2019.08.004.

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