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Reliability of measures of dynamic stability for the assessment of balance recovery after a forward loss of balance

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ABSTRACT

Background: Falls are common and serious events, which mostly occur during locomotion, that are associated with deficient dynamic balance. An experimental approach that simulates falling forward has become increasing popular to investigate dynamic balance. However, research has not been conducted to examine the test-retest reliability of this experimental approach.
Research question: What is the reliability of dynamic stability measures that are used for the assessment of balance recovery after forward loss of balance?
Methods: Nineteen healthy young adults (24.3 ± 2.8 yrs; nine females) volunteered for this study. They reported twice to the laboratory to perform two tests: (i) a stepping task, in which they were instructed to recover balance by taking a step after being suddenly released from an inclined forward position; and (ii) a standing task, in which we aimed to identify the maximum forward leaning angle they were able to compensate for without taking a step. Intra-class correlation coefficients (ICC) were calculated for the margin of stability (MoS) and spatiotemporal parameters for both tests.
Results: The reliability of the stepping task variables ranged from poor to excellent, with ICCs tending to increase with the number of trials included in the analysis. Intra-session analysis (one-way rm ANOVA) revealed a significant trial effect for the MoS, indicating that stepping responses changed across repeated trials. With respect to the standing task, test-retest reliability was only fair for the maximal initial leaning angle.
Significance: In essence, these results indicate that the inter-session reliability of the stepping task is acceptable, depending on the measures used and the number of trials conducted. However, one must be aware that behavioral adaptations arise with repeated exposure to simulated forward falls. Finally, this study's results suggest that the reproducibility of the standing task is limited.

1. Introduction

Balance describes the dynamics of body posture that prevent falling [1], and therefore, it is crucial for most activities of daily living and many sports [2]. However, due to the complexity and variety of structures involved in postural control processes, falls are common and serious events [3,4] that potentially lead to severe injuries. Hence, neuromechanical analyses of fall-related events address issues of particular interest to the scientific community, the public healthcare system, fall-prone persons, and patients who have been injured by falls.

Research has shown that most falls occur during locomotion, such as tripping or slipping while walking [4], and that the risk of falling is more closely related to dynamic than static stability [3]. In light of these findings, a large number of dynamic balance tests have been developed, including tests of gait perturbations, one-leg jump landings, and standing dynamic balance (for review, see [5,6]).

One of the latter tests assesses recovery behavior after a simulated forward loss of balance. Participants in this test stand motionless and lean forward at an inclined angle until a cable holding them suddenly releases, initiating a forward fall, after which they step rapidly to recover their balance. This experimental approach, which was introduced by Do et al. [7], is still widely used for scientific purposes [8–14]. It has revealed postural deficits in diverse populations (e.g., elderly and amputees), which indicate that the force potential of the leg extensor muscles [8], effective control of the body's center of mass [11], and step length and velocity [12] are important variables for recovering balance.

Unfortunately, to date, no research has been done to examine the reliability of this experimental approach, which should be an important

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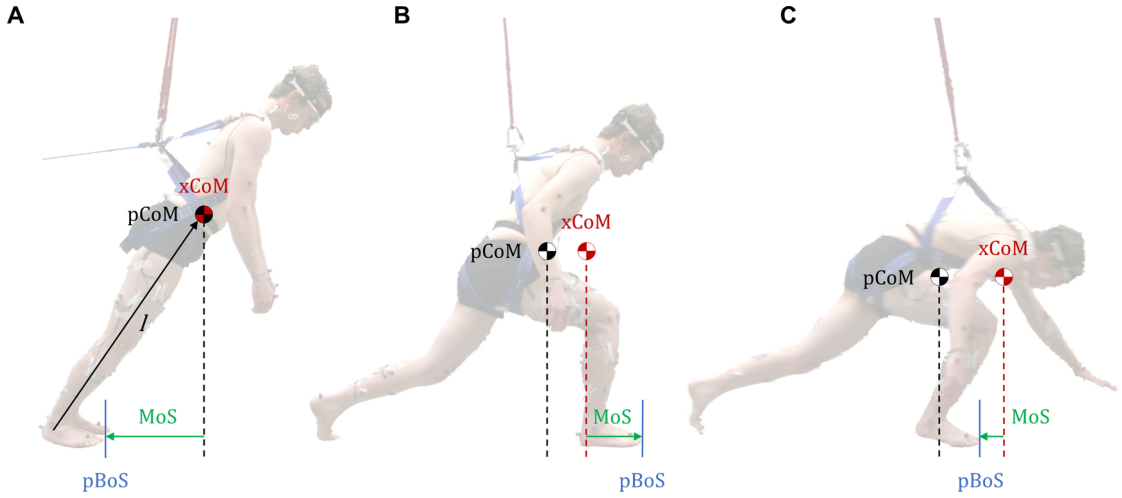

Fig. 1. Analysis of dynamic stability after forward loss of balance. Anteroposterior positions of the center of mass (CoM), extrapolated center of mass (xCoM), and anterior boundary of the base of support (pBoS). The margin of stability (MoS) refers to the position of the xCoM relative to the pBoS. Stability is maintained when the MoS shows positive values (arrow to the right), whereas a loss of stability is indicated by negative values (arrow to the left). **A**, initial forward-inclined position, where stability is guaranteed by the horizontal cable attached to the safety harness worn by the subject; **B**, successful balance recovery; **C**, unsuccessful balance recovery.

prerequisite for its use in scientific studies. Accordingly, the objective of this study was to investigate the reliability of the dynamic stability measures used to assess recovery of balance during forward loss of balance. Two experiments were designed and conducted for this purpose. The first experiment assessed the inter-session reliability of reactive stepping responses after simulated forward falls. Given that stepping responses previously have been shown to adapt across repeated trials [12], different numbers of trials were included in the analyses. The second experiment used a standing task to investigate the reproducibility of the maximum forward leaning angle at which the participants were able to compensate without taking a step.

2. Material and methods

2.1. Participants

Twenty-one healthy young adults (9 females and 12 males) participated in our study. Due to illness, two male participants were not able to perform the retest, leaving a total of nineteen participants (age = 24.3 ± 2.8 yrs, height = 1.73 ± 0.06 m, mass = 70.1 ± 8.3 kg). The participants were naïve to the experimental procedure and had no known muscular or neurological diseases that could have affected their ability to perform the tasks in the experiments. The study was approved by the Institutional Review Board and all the participants gave their written informed consent before participating in the study.

2.2. Experimental procedures

The test and retest were conducted one week apart at a similar time-of-day to investigate the reliability of our experiments. After signing the consent form, anthropometric measurements were taken and the participants were equipped with 39 passive reflective markers (diameter = 14 mm) that were placed on their skin in accordance with the Vicon Plug-In Gait full-body marker set (Vicon Motion Systems, Oxford Metrics Group; Oxford, UK). Then, participants "warmed-up" on a treadmill for 5 min, after which the two experiments of balance recovery were conducted. First, all participants performed the stepping task, whereupon the trials for the standing task were conducted.

Forward loss of balance was simulated in both experiments using the experimental approach introduced by Do et al. [7]. Accordingly, the participants were instructed to recover their balance after being suddenly released from an inclined forward posture [8]. The forward-inclined position in the present study was attained by a horizontal cable that was attached to a safety harness around the subject's trunk. The other end of the horizontal cable was connected to an electromagnetic system by which the investigators could manually release the cable (for detailed information, see [13]). The cable was released at a random time interval of 1–20 s in both experiments. However, different lean angles and balance-recovery strategies were used in the two experiments.

2.2.1. Stepping task

For the stepping task, participants stood on a force plate (AMTI, model BP600900, Advanced Mechanical Technology; Watertown, USA) and were moved in a forwardly inclined position that produced a horizontal force of 15% of the subject's body weight. This corresponded to a mean forward leaning angle of 23.4 ± 1.7°, which is very similar to the lean angles used in previous studies [8,9]. The subjects stood in this position with their heels touching the ground and their arms hanging at their sides before the forward fall was initiated, as described above. The participants were encouraged to restore their balance by taking a single rapid step to place their recovery limb properly in front of their other limb (Fig. 1). After one familiarization trial, five successful trials were conducted and recorded.

To reconstruct the initial position within and between sessions in the best possible way, prior to each trial one of the investigators visually controlled for the exact positioning of the feet on the force plate, the cable length, the fit of the safety harness as well as for the vertical and horizontal ground reaction forces.

2.2.2. Standing task

The aim of the second task was to identify the maximum forward leaning angle, and hence, the maximum margin of stability (MoS), for which the participants were able to compensate without the need to use a stepping strategy (change-in-support). Hence, the participants were allowed to use only an arm and/or hip and ankle strategy (feet-in-place). To do so, the forward leaning angle used for the stepping task was gradually reduced by shortening the horizontal cable (at two centimeter intervals) until the participants were able to recover their balance without taking a step. The lean angle was individually adjusted by this method for each participant, until there were three successful trials at the same leaning angle. The same procedure was done in the retest session. However, to verify the reproducibility of the maximum forward inclination, information of the test session (e.g. lean angle,

cable length, etc.) were blinded to the investigators.

2.3. Data acquisition and analysis

Kinematic data were collected by means of a 12-camera Vicon system (Vicon Motion System; Oxford Metrics Group, Oxford, UK) at a sampling rate of 200 Hz. The center of mass (CoM) was calculated based on the captured marker data and subject-specific anthropometric measurements, as described in the Vicon Plug-In Gait model (Nexus 1.85 version). All the data were processed using Matlab (version R2016a, The MathWorks; Natick, USA). In brief, time series were filtered using a fourth-order Butterworth low-pass filter (cut-off 15 Hz), on which the time points of release and touchdown, as well as different spatiotemporal and dynamic stability measures, were calculated.

Particularly during the stepping task, the participants' initial lean angle, step time (time interval from release until touchdown) and step length were calculated, along with the spatial margin of stability at touchdown (MoS_{TD}) and 500 ms after touchdown (MoS_{500}) [8,9,13]. The spatial MoS in the anteroposterior direction was calculated as proposed by Hof et al. [15]:

$$MoS = pBoS - xCoM$$

where $pBoS$ is the anterior boundary of the base of support, and $xCoM$ is the extrapolated CoM in the anteroposterior direction. The extrapolated CoM was calculated as follows:

$$xCoM = pCoM + \frac{vCoM}{\sqrt{g/l}}$$

where $pCoM$ is the anteroposterior component of the CoM, $vCoM$ is the anteroposterior velocity of the CoM, g is the acceleration of gravity, and l is the distance between the CoM and the center of the ankle joint in the sagittal plane.

The initial lean angle and the spatial margin of stability at release ($MoS_{Release}$) were determined for the standing task.

All valid trials (stepping task = five trials for each test session; standing task = three trials for each test session) were included in the analyses. In addition, different numbers of trials in the stepping task were included in the analysis to investigate whether inter-session reliability changes when more or less trials are conducted.

2.4. Statistics

All the statistical tests were performed using SPSS Statistics (version 24.0, International Business Machines Corporation; Armonk, NY, USA).

The inter-session reliability of both tasks was examined by calculating the means and standard deviations of the absolute differences between the test and retest, the 95% limits of agreement (LOA), and the intra-class correlation coefficients ($ICC_{3,1}$) for each variable [16].

One-way analyses of variance (ANOVA) with repeated measures (*trial* factor) was performed separately for each stepping task variable of the test and retest session to assess behavioral changes in balance recovery across the repeated trials within both session. Post-hoc tests of the differences between trials were analyzed using Bonferroni-corrected *t*-tests. The coefficient of variation (CV) was used to provide information about intra-session variability.

All the data are presented as means and standard deviations (mean ± SD). The magnitude of inter-session reliability was classified as follows: poor reliability = ICC < 0.4, fair reliability = 0.4 < ICC < 0.59, good reliability = 0.6 < ICC < 0.74, and excellent reliability = ICC > 0.75 [17]. Statistical differences are reported in terms of there their level of significance and effect sizes are indicated using the partial eta squared (small effect = 0.01 < η_p^2 < 0.06; medium effect = 0.06 < η_p^2 < 0.14; and large effect = η_p^2 > 0.14) [18,19]. The level of significance was set a priori to $p < 0.05$.

3. Results

3.1. Stepping task

Table 1 presents a summary of the results for the test-retest reliability of the stepping task. The ICCs of step length and step time revealed excellent and fair to good reliability, respectively, whereas the MoS_{TD} and MoS_{500} showed poor to good and good to excellent reliability, respectively. Overall, the ICCs tended to increase and the 95% LOAs tended to decrease as the number of trials increased. However, changes in LOAs were small and ICCs varied little when more than three trials were included in the analysis. The test-retest reliability for the initial lean angle was consistently poor, regardless of the number of trials included in the analysis.

Intra-session analyses of test and retest session revealed significant main effects of *trial* for the MoS_{TD} (test: $p = 0.001$, $\eta_p^2 = 0.22$; retest: $p < 0.001$, $\eta_p^2 = 0.24$) and MoS_{500} (test: $p = 0.002$, $\eta_p^2 = 0.21$; retest: $p = 0.030$, $\eta_p^2 = 0.16$). For the test session, post-hoc tests found statistically significant differences between trials 1 and 5 for the MoS_{TD} ($p = 0.009$) and between trials 1 and 5 ($p = 0.023$), 2 and 5 ($p = 0.006$), and 4 and 5 ($p = 0.034$) for the MoS_{500} (Fig. 2). For the retest session, post-hoc tests revealed statistically significant differences between trial 2 and 5 ($p = 0.044$), and 4 and 5 ($p = 0.020$) for the MoS_{TD} and between trials 3 and 5 for the MoS_{500} ($p = 0.019$).

The CVs across the test session's five trials were 4.60 ± 2.05% for step length, 5.06 ± 2.05% for step time, 21.08 ± 11.82% for the MoS_{TD}, and 10.44 ± 3.88% for the MoS_{500}.

3.2. Standing task

Table 2 summarizes the results for the test-retest reliability of the standing task. Though the reliability of the lean angle was fair, the $MoS_{Release}$ showed only poor reliability.

4. Discussion

The purpose of this study was to examine the reliability of measures of dynamic stability during the assessment of balance recovery after a forward loss of balance. First, we employed a stepping task to investigate the inter-session reliability of stepping responses after simulated forward falls and to determine the influence of the number of trials on reliability. Second, we used a standing task to investigate the reproducibility of the maximum forward inclination that can be compensated for without the need to take a step. The study yielded three main findings: (i) the inter-session reliability of the experimental setup and variables used to assess stepping responses depends on the variable measured and the number of trials, (ii) stepping responses change across repeated trials, and (iii) inter-session reliability is limited when examining the maximum forward inclination that participants are able to compensate for without the need to use a step.

4.1. Inter-session reliability of stepping responses is trial and variable dependent

The results of the stepping task revealed that inter-session reliability strongly differs among the variables and across the number of trials. Unexpectedly, lowest ICCs were found for the lean angle, even though the initial conditions were strictly supervised prior to each trial in both test sessions. Among others, the experimenters controlled for the exact positioning of the feet on the force plates, the length of the cable, a good fit of the safety harness as well as the horizontal and vertical ground reaction forces. This is reflected in the small standard deviations within the test sessions (approx. 0.6°) as well as the small difference between the sessions' mean values (approx. 0.3°; paired t-Test: $p = 0.625$). However, for some subjects there is a slight increase in the lean angle

Table 1
Means and standard deviations (mean ± SD) for the test and retest, means ($|\bar{D}|$) and standard deviations (SD $|\bar{D}|$) of the absolute differences between test and retest, 95% limits of agreement (LOA), and intra-class correlation coefficients ($ICC_{3,1}$) when different numbers of trials for the stepping task are compared.

Trials	Variable	Test	Retest	$\lvert\bar{D}\rvert$	SD $\lvert\bar{D}\rvert$	95% LOA	$ICC_{3,1}$ (95% CI)
1	Lean Angle [°]	23.44 ± 1.63	23.05 ± 1.62	0.38	2.14	−3.81–4.58	0.132 (-0.340–0.547)
	Step length [m]	0.86 ± 0.10	0.84 ± 0.13	0.02	0.07	−0.12–0.16	0.802 (0.536–0.918)
	Step time [s]	0.42 ± 0.06	0.42 ± 0.07	0.00	0.06	−0.12–0.13	0.515 (0.080–0.783)
	MoS_{TD} [m]	0.16 ± 0.05	0.15 ± 0.05	0.01	0.06	−0.10–0.13	0.303 (-0.156–0.657)
	MoS_{500} [m]	0.28 ± 0.05	0.26 ± 0.06	0.01	0.04	−0.07–0.10	0.678 (0.348–0.861)
1-2	Lean Angle [°]	23.34 ± 1.68	23.07 ± 1.71	0.27	2.31	−4.26–4.80	0.075 (-0.405–0.510)
	Step length [m]	0.86 ± 0.11	0.85 ± 0.14	0.01	0.06	−0.11–0.12	0.894 (0.749–0.958)
	Step time [s]	0.42 ± 0.07	0.42 ± 0.07	0.00	0.05	−0.10–0.09	0.592 (0.443–0.893)
	MoS_{TD} [m]	0.16 ± 0.04	0.15 ± 0.04	0.01	0.04	−0.07–0.10	0.445 (0.029–0.745)
	MoS_{500} [m]	0.28 ± 0.05	0.27 ± 0.06	0.01	0.04	−0.07–0.09	0.731 (0.429–0.887)
1-3	Lean Angle [°]	23.45 ± 1.72	23.13 ± 1.68	0.32	2.34	−4.27–4.91	0.052 (-0.422–0.492)
	Step length [m]	0.85 ± 0.11	0.85 ± 0.15	0.00	0.06	−0.12–0.12	0.898 (0.736–0.956)
	Step time [s]	0.42 ± 0.06	0.43 ± 0.07	0.01	0.05	−0.11–0.09	0.708 (0.392–0.876)
	MoS_{TD} [m]	0.15 ± 0.04	0.14 ± 0.04	0.01	0.04	−0.07–0.09	0.473 (0.056–0.754)
	MoS_{500} [m]	0.27 ± 0.04	0.27 ± 0.06	0.01	0.04	−0.07–0.08	0.723 (0.416–0.883)
1-4	Lean Angle [°]	23.50 ± 1.76	23.11 ± 1.64	0.39	2.31	−4.14–4.92	0.076 (-0.394–0.507)
	Step length [m]	0.86 ± 0.11	0.86 ± 0.15	0.00	0.06	−0.11–0.12	0.909 (0.778–0.964)
	Step time [s]	0.42 ± 0.06	0.43 ± 0.07	0.01	0.05	−0.11–0.09	0.719 (0.406–0.881)
	MoS_{TD} [m]	0.15 ± 0.04	0.14 ± 0.04	0.01	0.04	−0.07–0.09	0.456 (0.015–0.749)
	MoS_{500} [m]	0.27 ± 0.04	0.27 ± 0.06	0.00	0.03	−0.06–0.07	0.778 (0.510–0.908)
1-5	Lean Angle [°]	23.48 ± 1.77	23.23 ± 1.61	0.26	2.28	−4.20–4.72	0.103 (-0.380–0.530)
	Step length [m]	0.86 ± 0.12	0.85 ± 0.15	0.01	0.05	−0.10–0.11	0.919 (0.804–0.968)
	Step time [s]	0.42 ± 0.07	0.43 ± 0.07	0.01	0.05	−0.11–0.10	0.699 (0.367–0.872)
	MoS_{TD} [m]	0.15 ± 0.04	0.14 ± 0.04	0.01	0.04	−0.06–0.08	0.548 (0.148–0.797)
	MoS_{500} [m]	0.27 ± 0.05	0.26 ± 0.05	0.00	0.03	−0.06–0.06	0.817 (0.588–0.925)
2-5	Lean Angle [°]	23.50 ± 1.84	23.27 ± 1.63	0.23	2.34	−4.63–4.82	0.099 (-0.386–0.528)
	Step length [m]	0.86 ± 0.12	0.85 ± 0.15	0.00	0.06	−0.11–0.11	0.912 (0.806–0.969)
	Step time [s]	0.42 ± 0.07	0.43 ± 0.08	0.01	0.06	−0.12–0.11	0.689 (0.354–0.867)
	MoS_{TD} [m]	0.14 ± 0.03	0.13 ± 0.04	0.01	0.03	−0.06–0.07	0.607 (0.231–0.827)
	MoS_{500} [m]	0.26 ± 0.05	0.26 ± 0.06	0.00	0.03	−0.06–0.07	0.803 (0.555–0.919)
3-5	Lean Angle [°]	23.58 ± 1.90	23.33 ± 1.63	0.25	2.32	−4.30–4.80	0.145 (-0.341–0.560)
	Step length [m]	0.86 ± 0.12	0.85 ± 0.15	0.01	0.06	−0.12–0.13	0.900 (0.759–0.960)
	Step time [s]	0.42 ± 0.07	0.43 ± 0.08	0.01	0.07	−0.14–0.12	0.607 (0.220–0.828)
	MoS_{TD} [m]	0.14 ± 0.03	0.13 ± 0.04	0.01	0.04	−0.06–0.08	0.591 (0.201–0.820)
	MoS_{500} [m]	0.26 ± 0.05	0.26 ± 0.06	0.00	0.03	−0.06–0.07	0.791 (0.533–0.914)

MoS_{TD} = margin of stability at touchdown; MoS_{500} = margin of stability 500 ms after touchdown.

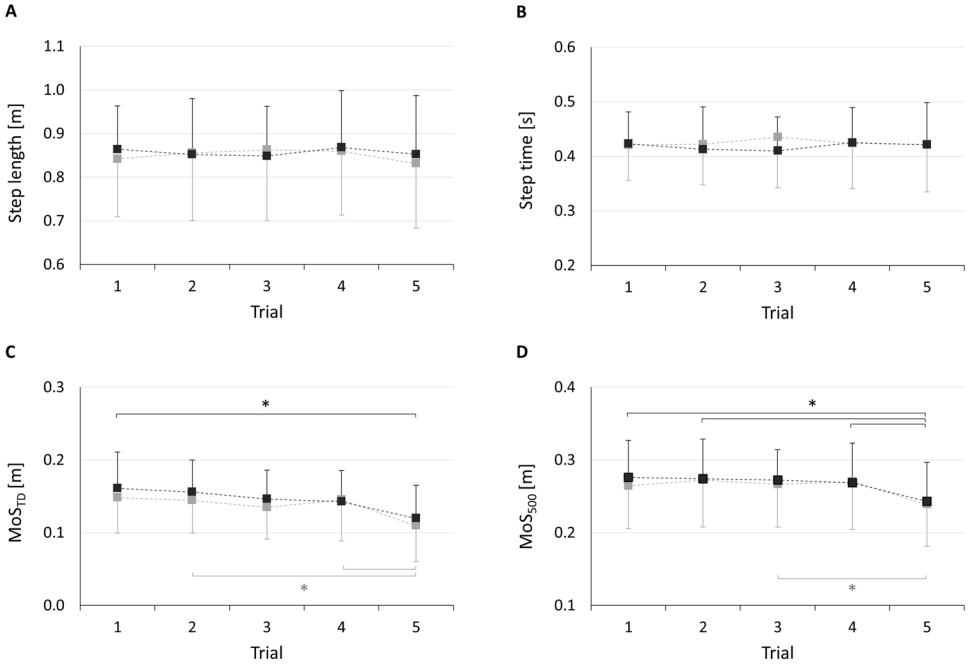

Fig. 2. Dynamic stability measures (mean ± SD) for the stepping task for trials 1–5 of the test session (black) and retest session (grey). **A**, step length; **B**, step time; **C**, margin of stability at touchdown (MoS_{TD}); **D**, margin of stability 500 ms after touchdown (MoS_{500}). *statistically significant ($p \leq 0.05$) as revealed by one-way, repeated-measures ANOVA and Bonferroni adjusted post-hoc *t*-tests.

Table 2
Means and standard deviations (mean ± SD) of test and retest, means ($|\bar{D}|$) and standard deviations (SD $|\bar{D}|$) of the absolute differences between test and retest, 95% limits of agreement (LOA), and intra-class correlation coefficients ($ICC_{3,1}$) for the standing task.

Variable	Test	Retest	$\|\bar{D}\|$	SD $\|\bar{D}\|$	95% LOA	$ICC_{3,1}$ (95% CI)
Lean Angle [°]	13.16 ± 1.17	13.12 ± 1.13	0.04	1.11	−2.14–2.22	0.547 (0.124–0.799)
$MoS_{Release}$ [m]	0.01 ± 0.02	0.01 ± 0.02	0.00	0.02	−0.04–0.04	0.317 (−0.165–0.670)

$MoS_{Release}$ = margin of stability at release.

from test to retest whereas for others there is a slight decrease. This finding paired with the constellation that between-subject variance is not substantially higher than within-subject variance finally has a negative impact on the ICC. Accordingly, an acceptable reproducibility of the experimental setup was not achieved.

Despite these limitations, excellent and fair to good reliability were found for step length and step time, respectively. Considering the dynamic stability measures, the MoS_{500} (good to excellent) showed higher ICCs compared to the MoS_{TD} (poor to good), suggesting that the kinematics of falling until touchdown may vary, but that participants are able to compensate for these differences in the post-touchdown period. Research has shown that the force potential of the leg extensor muscles [8] and effective control of the body's center of mass [11] are important factors contributing to recovery of balance.

Furthermore, our study showed that the ICCs tended to increase as the number of trials used to compare test and retest performance increased. Concomitantly, the 95% LOAs and the means and standard deviations of the absolute differences between the test and retest tended to slightly decrease as the number of trials increased. Nonetheless, the ICCs and LOAs showed very similar values for test-retest comparisons that included more than two trials. Bearing in mind the poor inter session reliability of the experimental setup, our study confirms the reproducibility of stepping responses after simulated forward loss of balance.

4.2. Stepping responses change across repeated trials

We found significant main effects of trials within both test sessions, indicating that stepping responses changed across repeated trials. Whereas no significant differences were found in spatiotemporal parameters, significant differences were found for the MoS_{TD} and the MoS_{500}. The magnitudes of both variables were significantly smaller during the last trial compared to at least one of the other trials. This could indicate a better prediction of adequate BoS and CoM control resulting from repeated exposure to the forward fall, which seems to have a similar time course during test and retest sessions. As there were only slight changes in the step length and step time, and post hoc analyses revealed marginal changes for global trunk angle at touchdown in the sagittal plane (trial 1: 30.25 ± 9.04°; trial 5: 31.13 ± 9.70°; rm ANOVA: $p = 0.681$, $\eta_p^2 = 0.033$), we assume that the decrease in the MoS is the combined effect of the above-mentioned factors along with a more efficient stepping strategy, reducing the forces and torques to the minimum necessary.

Previous studies found similar, but reversed, adaptations across repeated trials. A study by Barrett et al. [11] found the MoS to be significantly smaller for the first attempt compared to the following three attempts, and Carty et al. [12] observed adaptations from multiple- to single-step recovery following repeated exposure to forward falls in older adults. These adaptations were attributed to more effective whole-body CoM control [11] and increased BoS at touchdown [12]. As these adaptations occurred within a single test session, it was concluded that dynamic stability can rapidly be improved during repeated exposure to forward loss of balance. In conjunction with our data, which were obtained from young and healthy adults, it could be suggested that the adaptations take place in a way that achieves a sufficient (0.1 m > MoS > 0.2 m) but not a maximum amount of stability.

Based on these findings, one might conclude that at least one or two familiarization trials should be conducted to gain acceptable reliability and avoid learning effects. However, using familiarization trials is a particular issue of concern, as the aim of the existing experimental approach is to investigate dynamic balance in response to a sudden perturbation, i.e., falling forward. Repeated exposure from a static forward-leaning angle without any washout obviously diminishes the unanticipated nature of an everyday slip or trip. Therefore, the ecological validity of such an experimental approach to assess dynamic stability after a forward loss of balance seems to be limited. In light of this and taking into account the excellent reliability for comparisons of the latter trials between sessions (when the recovery technique is likely to be adapted), we would suggest that for validity reasons the first trials should be investigated and that any subsequent changes are likely to indicate adaptions in the stepping response.

4.3. Inter-session reliability is limited when examining maximum forward inclination

The third finding of our study is related to the inter-session reliability for the maximum forward leaning angle in the standing task. The results showed that the above-described procedure has limited reproducibility when its aim is to detect the maximum forward inclination that participants are able to compensate for without the need to take a step. The ICCs for $MoS_{Release}$ and lean angle underscore this finding in that they had poor to fair inter-session reliability. The differences between the ICCs for $MoS_{Release}$ and the lean angle are not intuitive at a first glance. However, there might be two possible explanations for this. First, the between-subject variance is considerably higher for the lean angle, which leads to an increase of the ICC given that the within-subject variance is similar for both variables. And second, as computation of the $MoS_{Release}$ is based on derivatives of the CoM, the noise of the signal and, in turn, the residual could be higher, finally decreasing the ICC for $MoS_{Release}$.

Notwithstanding these considerations, the present results suggest that caution is warranted when investigating recovery of balance from maximum forward-leaning angles. At the same time it also needs to be mentioned that, for both the standing task and the stepping task, the 95% LOAs and the means and standard deviations of the absolute differences had a very small range, which in turn, speaks favorably for both tests.

4.4. Study limitations

The main limitation is related to our study population. The sample was clearly homogenous in that it consisted of sports students between 19 and 31 years or age. Consequently, we are not able to draw conclusions about the reliability of the applied balance recovery tests in populations of different ages, sporting backgrounds, or skill levels. Furthermore, as we did not record the muscular activity of trunk and lower limb muscles, we are not able to draw any conclusions about anticipatory postural adjustments and muscle contributions to balance recovery.

5. Conclusion

In conclusion, our study demonstrates that the reliability of stepping recovery following forward loss of balance is excellent with respect to step length and the MoS_{500}, even though the initial conditions seem to be difficult to reproduce. Furthermore, the present findings indicate that adaptation may occur across repeated trials within one test session. This needs to be considered in the study design and use of familiarization trials in balance-recovery experiments. Latter aspect is of particular relevance, as the ecological validity of this approach is still a matter of discussion.

Conflict of interest statement

The authors disclose any financial or personal relationships with other people or organizations that could inappropriately have influenced this work.

CRediT authorship contribution statement

Steffen Ringhof: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization, Project administration. **Andrea Arensmann:** Methodology, Formal analysis, Investigation, Data curation, Writing - review & editing. **Thorsten Stein:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision.

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