Stability recovery performance in adults over a wide age range: A multicentre reliability analysis using different lean-and-release test protocols

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Abstract

The ability to effectively increase the base of support is crucial to prevent from falling due to stability disturbances and has been commonly assessed using the forward-directed lean-and-release test. With this multicentre study we examined whether the assessment of stability recovery performance using two different forward lean-and-release test protocols is reliable in adults over a wide age range. Ninety-seven healthy adults (age from 21 to 80 years) were randomly assigned to one out of two lean angle protocols: gradual increase to maximal forward-lean angle (maximal lean angle; n=43; seven participants were excluded due to marker artefacts) or predefined lean angle (single lean angle; n=26; 21 participants needed to be excluded due to multiple stepping after release or marker artefacts). Both protocols were repeated after 0.5 h and 48 h to investigate intra- and inter-session reliability. Stability recovery performance was examined using the margin of stability at release (MoS_{RL}) and touchdown (MoS_{TD}) and increase in base of support (BoS_{TD}). Intraclass correlation coefficients (confidence intervals at 95%) for the maximal lean angle and for the single lean angle were respectively 0.93 (0.89-0.96) and 0.94 (0.89-0.97) in MoS_{RL}, 0.85 (0.77-0.91) and 0.67 (0.48-0.82) in MoS_{TD} and 0.88 (0.81-0.93) and 0.80 (0.66-0.90) in BoS_{TD}, with equivalence being revealed for each parameter between all three measurements (p<0.01). We concluded that the assessment of stability recovery performance parameters in adults over a wide age range with the means of the forward lean-and-release test is reliable, independent of the used lean angle protocol.

Keywords: Stability performance, lean-and-release test, stability recovery stepping, reliability, falls.

Introduction

Falls are often caused by stability disturbances and remain a global health issue that majorly affects older but also middle-aged adults and often lead to severe health conditions, or even death (Burns and Kakara, 2018; Peeters et al., 2018; Terroso et al., 2014; Stenhagen et al., 2014). It is therefore important using reliable assessments for the recovery performance after stability disturbances to identify individual deficiencies or to classify the effectiveness of acute or long-term interventions on stability recovery performance.

The increase in base of support (BoS) i.e., to control the centre of mass (CoM) within the BoS, is one of the main mechanisms to recover stability after disturbances (Hof, 2007). Stability recovery performance can be determined using the margin of stability concept (MoS; Hof et al., 2005) that provides information about the position of the CoM considering its velocity (extrapolated CoM; X_{CoM}) in relation to the boundaries of the BoS, where the X_{CoM} being outside the BoS represents an instable state of the body, and vice versa. To identify individual deficiencies in stability recovery performance after sudden stability loss in the anterior direction, the *lean-and-release* test has often been applied on adults over a wide age range (Arampatzis et al., 2008; Carty et al., 2012; 2015; Karamanidis and Arampatzis, 2007; Karamanidis et al., 2008). These studies revealed clear deficits in stability recovery performance along with the inability to recover stability with a single step due to an insufficient (slow and low) increase in BoS with ageing. This age-related decline could even be associated to future falls in community-dwelling older adults (Carty et al., 2015; Okubo et al., 2017). Furthermore, the test has been applied to monitor acute effects of muscle-fatigue (Mademli et al., 2008; Walsh et al., 2011) or training interventions (Aragão et al., 2011; Arampatzis et al., 2011; Bohm et al., 2020) on stability recovery performance as well as to examine the inter-task transfer of acquired fall-resisting skills from gait trip-like perturbation training (König et al., 2019).

Lean-and-release test protocols often differ depending on the study design. Several studies investigated the maximal lean angle from which one can recover with a single step (Aragão et al., 2011; Arampatzis et al., 2011; Bohm et al., 2020; Hamed et al., 2018). Repeated exposures to sudden stability loss in the anterior direction however seem to lead to immediate improvements in recovery stepping performances (Carty et al., 2012; Ringhof et al., 2019). Even small differences in stepping responses possibly evoked by task repetition could affect the ability to recover stability with a single step (Carty et al., 2012) i.e., the criterion to determine the maximal lean angle. Thus, it remains unclear yet whether such protocol is reliable. An alternative protocol is a sudden anterior stability loss from one or more predefined lean angles usually following a few practice trials (Carty et al., 2012; 2015; Karamanidis and Arampatzis, 2007; Karamanidis et al., 2008; Mademli et al., 2008). A recent study conducting consecutive exposures to anterior stability loss on young adults from a single lean angle indicated to an appropriate consistency and no day-to-day differences in the increase in BoS and in the MoS measured at 500ms after touchdown (Ringhof et al., 2019). However, the authors revealed less reliability for the assessment of task demand (lean angle) and MoS at the instant of touchdown. When furthermore considering several trial repetitions (intra-session) and the focus on one age group only (young adults), yet it remains unclear whether the assessment of stability recovery performance using only one exposure to sudden stability loss from a predefined lean angle is reliable across adults over a wide age range.

With this multicentre study we asked whether the assessment of main parameters used to determine stability recovery performance i.e., MoS at release, MoS and BoS at touchdown, conducting the lean-and-release test is reliable in adults over a wide age range (21 to 80 years; *n*=97). We separately investigated two lean-and-release test protocols i.e., determination of the maximal lean angle from which a participant is still able to recover stability with a single forward step (maximal lean angle protocol) and a single exposure to stability loss from a predefined lean angle (single lean angle protocol).

Methods

Participants and experimental design

The study took place at three laboratories (Humboldt-Universität zu Berlin, German Sport University Cologne and Robert-Bosch-Hospital in Stuttgart). A total of 97 adults ranging from 21 to 80 years of age were investigated. They were healthy and moderately physical active (e.g., regular weekly exercise). Exclusion criteria were any neurological or musculoskeletal injuries or impairments of the lower limbs limiting movement. After providing written informed consent, participants were randomly assigned to either a maximal lean angle protocol, or a single lean angle protocol (maximal or single for Berlin: n=18 or 15; Cologne: n=15 or 17; Stuttgart: n=17 or 15). Both protocols were repeated once within a single session (Baseline and Post 0.5h) and after two days (Post 48h) to determine intra- and inter-session reliability. At all measurement timepoints, participants wore the same pair of their own non-slippery sports/leisure shoes. The study was approved by the respective local ethical committees (approval numbers for Cologne: 141/2017; Berlin: EA/082/15; Stuttgart: 266/2016MP2) and met all requirements for human experimentation in accordance with the Declaration of Helsinki (World Medical Association, 2013).

Figure 1

Determination of the maximal forward-lean angle

Participants were always protected by a safety harness connected to an overhead track, allowing for full range of motion in anterior and lateral directions while preventing contact of the body with the ground (except for the feet). While standing on a force plate mounted in front of a second one (1080Hz, 60x90cm, Kistler, Winterthur, Switzerland or 1000Hz, 40x60cm, AMTI, MA, USA: depending on the laboratory) with their feet in parallel at hip-width and flat on the ground, participants were set in a forward-inclined position via an inextensible horizontal cable attached to a belt around the participant's pelvis (Karamanidis et al., 2008; Fig. 1) and at the other end either to a custom-built pneumatic-driven break-and-release system in Cologne (Karamanidis and Arampatzis, 2007), to a wall-mounted rail incorporating a snap-shackle-release system in Stuttgart, or to a wall-mounted electromagnet in Berlin (Hsiao and Robinovitch, 1999). The level of cable attachment differed between laboratories i.e., chest-level in Berlin versus level of pelvis/umbilicus in Cologne and Stuttgart. The initial lean angle (23±2% of body mass for participants ≤36 years, and 10±2% for ≥43 years accounting for the task demand in relation to the participants' age; Karamanidis and Arampatzis, 2007; Madigan, 2006) was controlled via a load cell (depending on the laboratory either custom-made 0-1kN, or Megatron 0-5kN; MEGATRON Elektronik GmbH & Co. KG, Munich, Germany) incorporated into the horizontal cable. Without any warning, the cable was suddenly released, randomly between 10 to 30 seconds. The lean angle was increased gradually by 3% if the participants were able to recover stability with a single step as instructed priorly (Karamanidis and Arampatzis, 2007). If the participants needed more than one step or a safety harness support (>20% of body mass determined by a second load cell incorporated into the harness suspension cable, i.e., multiple stepping; Karamanidis et al., 2008; Cyr and Smeesters, 2009), this trial was repeated. The measurement was terminated if the participants needed more than one step to recover stability in two consecutive trials. The last lean angle linked to a successful single step recovery was defined as the maximal lean angle. Please note that there were no prior practice trials performed for all measurement time points.

Single exposure to stability loss from a predefined forward-lean angle

Safety assumptions, measuring equipment, procedure for the initial placement of the participants and task instructions matched the maximal lean angle protocol (see *Determination of the maximal lean angle* and Fig. 1). Participants were released only from a single predefined lean angle corresponding to 23±2% of body mass. The forward-lean angle was chosen according to our previous results showing older adults still being able to recover stability from lean angles of approximately 20% of body mass

(Karamanidis et al., 2008). Only at Baseline but not for Post 0.5h and Post 48h, all participants performed three prior practice trials at 20±2% of body mass to familiarise with the task.

Data collection and processing

To quantify stability recovery performance for the two protocols, reflective markers were tracked via an optical motion capture system using ten infrared cameras (120 or 250Hz, depending on the laboratory; Nexus; Vicon Motion Systems, Oxford, UK). The markers defined the foot, shank, thigh, trunk, upper and lower arm, hand, and head (Bierbaum et al., 2013; Fig. 1). Two events were identified for both test protocols: (a) release of the supporting cable determined by a 50% reduction in the leaning force signal provided by the incorporated load cell via a synchronized analogue TTL signal, and (b) foot touchdown of the recovery step determined via the vertical ground reaction force of the second force plate (threshold ≥5N). The anterior MoS was determined at cable release (MoS_{RL}) and foot touchdown (MoS_{TD}) of the recovery step, calculated in accordance with Hof and colleagues (2005) as the differences between the extrapolated CoM (X_{CoM}) in the anterior direction and the anterior boundary of the BoS (P_{BoS}; see Fig. 1). Segment masses and CoM locations were calculated based on the data reported by Dempster et al. (1959) and the position of the whole body's CoM in the 3D space was calculated according to Winter (1979), using a custom-made MATLAB script (2020b, MathWorks®, Natick, MA, USA). The BoS at touchdown (BoS_{TD}) i.e., the distance between the anterior and posterior boundaries of the base of support, was determined using the vertical projection of a heel marker of the trailing foot and the tip of the shoe of the recovery foot, considering the distance of a metatarsal marker to the anterior boundary of the shoe (measured during preparation).

Statistics

For both protocols, three measurement trials (Baseline, Post 0.5h and Post 48h respectively) were included. Normality and variance homogeneity of anthropometrics (body height, body mass, body mass index) and the analysed stability control parameters (MoS_{RL}, MoS_{TD}, BoS_{TD}) were checked using the Shapiro-Wilk test and Mauchly's sphericity test (p>0.05). Body heights, body masses and body mass indexes of all participants separated by protocols and centres were statistically compared using separate one-way ANOVAs or Kruskal-Wallis tests, with Bonferroni-adjusted or Mann-Whitney-U *post hoc* tests performed in the presence of significant main effects. Potential differences in all analysed stability control parameters between repeated measurements were examined using separate (for both the maximal and single lean angle protocol) one-way repeated measures analyses of variance (ANOVA) with trials as within-subject factor. In the presence of significant main effects, Bonferroni-adjusted *post hoc* tests for pairwise comparison were performed to locate potential differences. Two-way mixed model intraclass correlation coefficients (ICC, absolute agreement, and single measures) over all trials were calculated, with confidence intervals at 95% (Koo and Li, 2016). ICC were defined as "poor" (<0.50), "moderate" (0.50-0.75), "good" (0.75-0.90) and "excellent" (>0.90) to interpret reliability (Portney, 2020). Root mean square errors (RMSE) were computed to determine the average dispersion of the observed trial from the previous one and reported as a range between all trials. To argue for the absence of an effect being large enough to state a significant discrepancy between trials, two one-sided tests (TOST) for equivalence were performed. According to Lakens (2013, 2017), the difference between dependent trial means, and respective confidence intervals at 95%, were tested with a standardised lower (Δ_L) and upper (Δ_U) bound of equivalence based on Cohen's *dz* that was calculated from current raw data. The level of significance was set at α=0.05. All statistical and non-statistical analyses as well as descriptive computations were performed using SPSS Statistics (v26, IBM, Chicago, IL, USA) and MATLAB (2020b, MathWorks®, Natick, MA, USA).

Results

Maximal lean angle

Due to significant marker artefacts during the measurements, data of seven participants were excluded hence 43 participants (19 females; 29 to 77 years) were considered for the statistical analyses. Body height, body mass and body mass index did not significantly differ between the centres (Berlin: 172.9±9.3cm, 75.0±11.6kg and 25.0±2.9kg/m^2; Cologne: 172.3±13.1cm, 75.1±15.8kg and 25.0±2.7kg/m^2; Stuttgart: 172.9±7.7cm, 77.3±9.4kg and 25.9±2.5kg/m^2). Regarding the MoS_{RL}, an excellent ICC of 0.93 (CI_{95} [0.89-0.96]; Table 1) was computed over all trials, with RMSE ranging between 3.3 and 5.1cm. Although the TOST at 95% confidence revealed an effect statistically different from zero for the MoS_{RL} between Baseline and Post 48h (Fig. 2), there was no significant difference when using a one-way ANOVA, neither between Baseline and Post 0.5h or Post 0.5h and Post 48h (Fig. 3). Moreover, TOST showed statistically significant (p<0.01) equivalence between all pairs of trials. Furthermore, there were no significant differences in the MoS_{TD} between all trials, showing good ICC of 0.85 (CI_{95} [0.77-0.91]), RMSE ranging between 4.9 and 7.1cm, and significant equivalence (p<0.001). Good reliability (ICC of 0.88; CI_{95} [0.81-0.93]) was also revealed for the BoS_{TD} whilst an absence of significant differences, with RMSE ranging between 7.4 and 8.4cm, and statistical equivalence (p<0.001) between all trials.

Table 1

Figure 2

Figure 3

Single lean angle

Data of ten participants could not be analysed appropriately and were excluded from the statistical analysis. Only body mass but neither body height nor body mass index of the included 41 participants (15 females; 22 to 70 years; Berlin: 172.2±6.7cm, 68.7±9.2kg and 23.1±1.9kg/m^2; Cologne:

175.7±8.1cm, 79.8±11.8kg and 25.8±2.6kg/m^2; Stuttgart: 172.4±7.0cm, 80.9±19.2kg and 27.1±5.4kg/m^2) significantly differed between Berlin and both Cologne (p=0.020) as well as Stuttgart (p=0.020). Please note that 13 out of 15 adults (61-70 years) required multiple steps during the single lean angle protocol at all measurements. Thus, those data were non-statistically observed and excluded from further processing as we investigated continuous variables which are affected differently between single and multiple stepping responses. When considering the data of adults (21 to 60 years; n=26) who were able to successfully recover stability with a single step, there were no significant differences in MoS_{RL} between all trials (Fig. 4), with an excellent ICC of 0.94 (CI_{95} [0.89-0.97]; Table 1) and RMSE ranging between 1.8 and 2.3cm. The MoS_{TD} neither differed between all trials, showing a moderate ICC of 0.67 (CI_{95} [0.48-0.82]) and RMSE ranging between 5.1 and 6.8cm. The BoS_{TD} showed good reliability (ICC of 0.80; CI_{95} [0.66-0.90]), with no differences between all trials and RMSE ranging between 6.7 and 8.2cm. For MoS_{RL}, MoS_{TD} and BoS_{TD}, TOST revealed significant (p<0.01) equivalence between all trials (Fig. 5). We furthermore observed 13 out of 15 older adults who were not able to recover stability with a single step from the single pre-defined lean angle (single lean angle protocol) in all trials revealing an overall consistency of recovery stepping behaviour i.e., multiple stepping.

Figure 4

Figure 5

Discussion

In this multicentre study we examined whether the assessment of stability recovery performance parameters in adults over a wide age range is reliable if conducting a maximal forward-lean angle approach as well as a single exposure to sudden anterior stability loss from a predefined lean angle. For both lean angle protocols, we revealed statistically appropriate consistency and equivalence with the absence of any relevant differences in all analysed parameters. The results indicate that the lean-and-release test is a reliable assessment to potentially identify individual deficiencies or to classify the effectiveness of acute or long-term interventions on stability recovery performance.

Maximal lean angle

With the MoS_{RL} considered as the main criterion, the maximal lean angle protocol has often been used as a standardised assessment method to identify age-related deficiencies or intervention effects on stability performance. Previous studies reported an improved stability performance in older adults following several months of stability and/or strength training (more negative MoS_{RL} ranging on average from 2.8 to 6.6cm at post compared to pre intervention) i.e., they were able to successfully recover stability with a single step from a more inclined and unstable position (Arampatzis et al., 2011; Bohm et al., 2020; Hamed et al., 2018). The current study revealed excellent reliability (ICC of 0.93) for the MoS_{RL} in adults over a wide age range (29 to 77 years), with lower differences (1.1cm on average) compared to the intervention studies, and overall significant equivalence between all trials. This strengthens the outcomes of previous findings demonstrating differences, indicating that those were caused by the conducted intervention rather than biased by task adaptation or drawbacks related to the reliability of measurements.

We terminated a measurement after two consecutive failures of single step recovery occurred. Respectively, some participants might have learned due to task repetitions (Carty et al., 2012; Ringhof et al., 2019) with the same lean angle. However, we demonstrated excellent reliability in the MoS_{RL} using the same procedure for all measurements indicating that the identified individual maximal lean angle can be postulated as an ultimate task demand to test recovery performance in a reliable manner. This was further supported by good consistency (ICC ranging from 0.85-0.88), non-significant differences and equivalence between all trials revealed for the stability performance at touchdown (BoS_{TD} and MoS_{TD}) i.e., the ability to recover stability from similar maximal lean angles at all trials always came along with similar step lengths and control of the CoM in relation to the BoS. Thus, we state that using the maximal lean angle protocol is a reliable assessment to determine the maximal capability of stability recovery performance in adults over a wide age range.

Due to low and unequal sample sizes of and between different age groups we did not consider an age-related contribution to the reliability results for the maximal lean angle protocol. However, when pooling all participants above 43 years (n=22) according to the chosen single lean angle protocol that accounted for a lower initial task demand for such age cohorts, we found significant (p<0.001) and good ICC for all analysed parameters (range between 0.86 and 0.90). Moreover, for this sub-pool of adults above 43 years we revealed an average RMSE over trials of 6.3cm in the MoS_{TD}, that was similar to the average error between trials of all participants under 36 years (6.7cm; n=21). Thus, we believe that pooling all participants for the analyses did not cause a bias related to the current reliability and that age had no relevant effect on the main outcomes of the current study.

Single lean angle

Our results revealed excellent reliability in the MoS_{RL} and overall equivalence, indicating that the lean angle was effectively controlled across all trials (mean and RMSE on average for all trials: -18.6cm and 2.0cm). It is important to note that the standard deviations of the MoS_{RL} were rather high (on average for all trials: 5.8cm) assuming a higher inter-subject variability potentially caused due to heterogeneous body configurations (body height may influence MoS_{RL}). However, since body heights were homogenous between the participants, the high standard deviation can rather be explained by laboratory-related differences in the attachment level of the supporting cable and incorporated load cell respectively i.e., a more proximal attachment (level of umbilicus or higher) required the participant to lean more forward and led to lower values in the MoS_{RL}. Such a higher demand on stability recovery performance caused mostly all older adults (n=13 out of 15; 61 to 70 years) failing to recover stability with a single step during the single lean angle protocol in all trials. Nevertheless, since all younger and middle-aged adults were able to recover with a single step, the demand seemed to be appropriate for these age populations and furthermore the assessment was highly reliable. In contrast to our findings, Ringhof and colleagues (2019) recently revealed poor between-session reliability for the demand on stability recovery performance (measured in degrees) following exposure to stability loss from a single predefined lean angle (15% of body mass) in young adults. These results may be difficult to compare with the current outcomes as we used a different parameter for the task demand i.e., MoS. However, when considering that the MoS_{RL} is mainly used to interpret the demand on stability recovery performance, we confirmed this was reliably assessable among adults over a wide age range.

Since the single lean angle protocol requires a constant demand on stability recovery performance within each execution (i.e., a pre-defined MoS_{RL}), the MoS_{TD} and BoS_{TD} have commonly been used as the main criteria to determine stability performance. A recent study indeed showed an improved stability performance (MoS_{TD}) after a single trial repetition in younger and middle-aged adults, without any prior practice trials performed at Baseline (ΔMoS_{TD} on average for both age-groups: 3.8cm, $p<0.01$; RMSE: 7.8cm; = 27; König et al., 2019). In contrast to those findings the current study did not reveal significant differences between the means of all trials in the MoS_{TD}, particularly of Post 0.5h versus Baseline (ΔMoS_{TD}: 0.4cm, with a comparably lower RMSE of 5.1cm on average respectively). This could be explained mainly by the constant BoS_{TD} between trials revealed in the current study. As our participants performed three practice trials prior to the Baseline measurement, we cannot confirm the absence of task adaptations which might have been occurred due to immediate task repetition during Baseline. But we proved the current protocol to be a reliable assessment approach without performing any further practice trials prior to Post 0.5 and Post 48h. Yet a control group is required essentially to exclude bias caused by rapid adaptation due to consecutive repetition of a novel stability task (König et al., 2019).

The different levels of cable attachment i.e., chest versus umbilicus versus pelvis, led to different stability demands according to one standardised percentage of body mass. Thus, it might have caused a drawback to determine reliability of the single lean angle protocol and stability performance in older adults in a standardised manner. However, although their demand on stability (MoS_{RL} on average for all trials: -20cm; *n*=15) might have contributed to an inability to recover stability with a single step, multiple stepping was observed to be consistent during all trials for 13 out of 15 older adults, indicating to no functionally relevant learning due to task repetition and hence to a reliable assessment of stability performance that has previously been shown to predict future falls (Carty et al., 2015). Nevertheless, to overcome any influence of different cable-attachments we postulate considering the initial state of body configuration with the means of the MoS instead of relying solely on the percentage of body mass for the assessment of stability recovery performance using a single lean angle approach.

We concluded that the assessment of stability recovery performance parameters in adults over a wide age range using the forward lean-and-release test is reliable, independent of the used lean angle protocol. Our results further strengthen the use of an exposure to stability loss from a single predefined lean angle, as this protocol being less time-consuming and less demanding could especially be beneficial to test stability recovery performance in clinical settings.

Conflict of interest statement

All authors hereby declare no known financial and personal relationships with other people or organisations that could inappropriately have influenced or biased the current manuscript.

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Table 1: Intraclass correlation (ICC) coefficients with 95% confidence intervals (CI_{95}) and range of root mean square errors (RMSE; in cm) for margin of stability at release (MoS_{RL}) and at touchdown (MoS_{TD}) as well as the base of support at touchdown (BoS_{TD}) between the measurements (Baseline, Post 0.5h and Post 48h) for the maximal and single lean angle protocols (*n*=43 and *n*=26 respectively).

		Maximal lean angle (*n* = 43)		Single lean angle (*n* = 26)	
	Measurements	**ICC [CI_{95}]**	**RMSE (cm)**	**ICC [CI_{95}]**	**RMSE (cm)**
MoS_{RL}	Baseline vs. Post 0.5h	0.96 [0.93-0.98]	3.3	0.95 [0.90-0.98]	1.8
	Post 0.5h vs. Post 48h	0.93 [0.88-0.96]	4.0	0.95 [0.90-0.98]	1.8
	Baseline vs. Post 48h	0.90 [0.81-0.94]	5.1	0.92 [0.84-0.97]	2.3
MoS_{TD}	Baseline vs. Post 0.5h	0.85 [0.74-0.92]	6.0	0.70 [0.43-0.85]	5.1
	Post 0.5h vs. Post 48h	0.90 [0.83-0.95]	4.9	0.66 [0.38-0.83]	5.1
	Baseline vs. Post 48h	0.80 [0.66-0.89]	7.1	0.66 [0.39-0.83]	5.8
BoS_{TD}	Baseline vs. Post 0.5h	0.91 [0.83-0.95]	7.4	0.82 [0.63-0.91]	6.7
	Post 0.5h vs. Post 48h	0.88 [0.78-0.93]	7.8	0.80 [0.61-0.91]	7.3
	Baseline vs. Post 48h	0.85 [0.74-0.92]	8.4	0.78 [0.57-0.89]	8.2