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Method Article

Forward functional stability indicator (FFSI) as a reliable measure of limits of stability

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A B S T R A C T

Functional stability has been studied in diverse populations, yet the possibility to compare the results across them and the knowledge about actual performance referenced to the maximum capacity is limited. Our aim was to improve the functional limits of stability testing and introduced Forward Functional Stability Indicator (FFSI) as a reliable measure of functional stability. The study participants were not able to cross the projected forward anatomical stability limit (FASL). It is located at the level of first metatarsophalangeal joints and should be considered a mechanical limit of the maximal voluntary centre of foot pressure (COP) excursion (MVE). It was only true when the whole feet were in contact with the ground. There were statistically significant differences in limits of stability (LOS) test results in the conditions when the heels were raised and the toes muscles were contracted isometrically. The proposed forward functional stability indicator (FFSI) is a highly reliable measure of functional stability, which provides information about the actual performance with reference to maximum capacity and is easy to compare across normal and clinical populations.

- The proposed forward functional stability indicator (FFSI) is a highly reliable measure of functional stability.
- FFSI provides information about the actual performance with reference to maximum capacity and is easy to compare across normal and clinical populations.
- The forward anatomical stability limit (FASL) is located at the level of first metatarsophalangeal joints and should be considered a mechanical limit of the maximal voluntary centre of pressure (COP) excursion when certain measurement criteria are met.

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A R T I C L E I N F O
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Specification Table

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More specific subject area:	Biomechanics, Posture Control
Method name:	Forward Functional Stability Indicator (FFSI)
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Resource availability:	N/A

Method details

Rationale

Functional balance, together with static balance in quiet standing, is one of the most studied subjects in diverse populations. During the common functional balance procedures, the stability is tested at its conceptual limits. These limits of stability (LOS) are reported as functional reach distance, actual displacement of the center of gravity/center of foot pressure (COG/COP) or more often referred to as a percentage of the base of support (foot length) while maintaining an upright posture [1–7].

Occasionally, when comparing the results of two people with different foot length, that are based on the simple displacement of the COP, the results would be misleading due to these differences. Therefore, a larger COP displacement in the LOS test might indicate better stability (broader stability limit) or it can simply mean a larger foot. This problem is dealt with when the maximum voluntary COP excursion (MVE) would be standardized by the foot length (base of support). Unfortunately, such a result does not inform about the actual performance capacity of the tested subject, i.e. whether the outcome is positive or negative.

Although the functional stability limits has have been already defined in several studies, we would like to suggest a simple yet significant improvements in the method of the stability limits testing, that would eliminate misinterpretation of the results and would allow comparisons between populations.

We postulate that the stability limits are possible to be precisely established for every subject individually and are constant for them. We hypothesised that the forward functional stability limit is located at the line connecting the first metatarsophalangeal joints. This idea was already suggested by Błaszczyk et al. [8] as the real landmark for detecting the extreme mechanical limit of the forward leaning, however, it was not experimentally proved or tested. The momentum caused by the forward shift of the whole body weight without taking a step usually leads to tiptoe standing. This is possible thanks to the built of the foot with metatarsophalangeal joints which elicit rotational movement around the joint axes in such situation. We consider this landmark very important from the functional point of view and the reason why it should be considered a landmark for functional stability.

The limits of stability (LOS) test was used to evaluate functional stability and was conducted as described in the study by Juras et al. [9] The original method implies participants to be instructed to stand barefoot on a force platform with their feet in a comfortable position, and their arms along their sides throughout the test. Their gaze fixation point is placed 2 m away from the subjects on the wall in

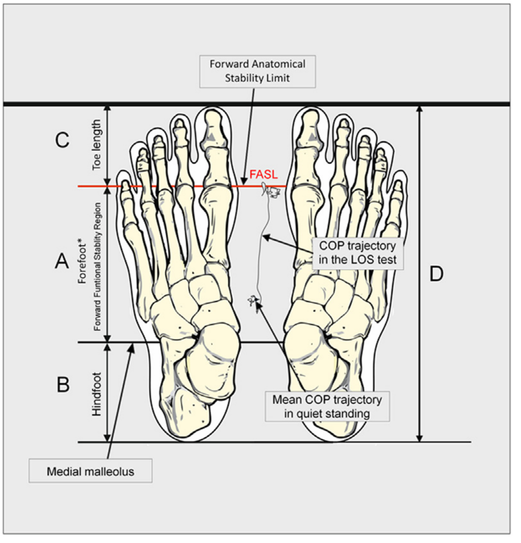

Fig. 1. Anthropometric measures of the feet and forward anatomical stability limit (FASL), *forefoot measured from the fifth metatarsophalangeal joints to the center of the medial malleolus.

front of them at the eye level. Each trial in the procedure starts with 10 s of quiet standing, after which an acoustic signal is triggered to initiate the whole body forward leaning phase without changing the base of support (no step or foot rise is allowed). The subjects execute the leaning movement at their own pace until they reached their maximal range. Only the movement at of the ankle joints is allowed (i.e. no angular change in the hips joints). The maximal leaning position achieved by the subject should be maintained until the end of the trial (15 s on average). Therefore, the test consists of three distinct phases: 1 – quiet standing, 2 – leaning forward, 3 – maintaining the inclined position. Time of each trial is 30 s, after which the subject returns to the initial position and steps off the platform. In order to strengthen the reliability of the results the test should be repeated three times. The improved procedure imposes calculation of the exact position of the antero-posterior (A/P) COP relative to the center of the platform. For this purpose a 1 cm thick line is drawn 10 cm away from the front edge of the platform. Subjects are asked to place their big toes so that they were tangential to the drawn line.

In the proposed method the COP data is referred to individual anthropometric measures of the feet taken with a spreading caliper. Two joints in the foot (the upper talonavicular joint and the fifth metatarsophalangeal joint) define the axes of rotation in the sagittal plane. This is the reason to used them in defining individual parts of the foot (Fig. 1). They are measured as follows: A – length of the forefoot (distance from the medial malleolus to the first metatarsophalangeal joint), B – length of hind foot (the distance from the most backward point of the heel to the medial malleolus), D – length of the foot (the distance from the most forward to the point on the calcaneus to the foremost point on the foot), C – length of the toe (the distance from the first metatarsophalangeal joint to the foremost point on of the big toe).

Apparatus

The functional stability is tested with the use of the force platform (Accugait type; AMTI, Watertown, MA, USA). The sampling frequency of the platform is set at 100 Hz. A low-pass 4-order Butterworth filter with a sampling frequency of 7 Hz is used for the raw platform data. The calculated center of foot pressure (COP) data are subject to further analysis using the MatLab (Mathworks, Natick, MA, USA).

Table 1
The characteristics of the study participants.

variable	all (n = 30) mean ± SD	women (n = 15) mean ± SD	men (n = 15) mean ± SD
age [years]	21 ± 1	21 ± 1	21 ± 0.5
body height [cm]	172.2 ± 10.4	164. 6 ± 7	179.7 ± 7.2
body weight [kg]	67.2 ± 13.4	57.3 ± 5	77 ± 11.9
foot length [cm]	24.9 ± 1.7	23.7 ± 1.1	26.1 ± 1.5
the length of the big toe [cm]	6.8 ± 0.8	6.4 ± 0.5	7.2 ± 0.8
the length of the forefoot [cm]	13.8 ± 1.1	12.4 ± 0.6	13.9 ± 0.8

Method validation

Subjects

Thirty young, healthy participants voluntarily took part in the study (Table 1). None of the participants reported musculoskeletal or neurological disorders, nor they had any orthopaedic injuries in the last 6 months. The informed written consent was obtained from the participants. The study design and the procedures used were approved by the Institutional Review Board.

The test was conducted in three conditions. The first involved whole feet adhesion to the platform during the trial, namely the lift of the heels was not allowed. In the second condition, participants were instructed to bend and isometrically contract toes. In the third condition, the subjects were asked to raise the heels during the leaning forward phase (Fig. 2). The order of the conditions was selected randomly for the subject. Two familiarization trials were allowed for each condition. There was a two minute rest break between the condition trials in order to avoid fatigue. The subjects were asked to step off the platform between the trials.

Data processing

The most important and novel in this study is the approach that has been used in the LOS test data processing. The calculated COP data were subjected to further analysis using the MATLAB software. The following two variables of the leaning range were calculated: a) standard maximal voluntary COP A/P excursion (MVE) being the distance in cm between the average COP position in the first phase of the LOS test, corresponding to the quiet standing, and the average COP position in the third test phase, corresponding to MVE in the forward leaning position; b) the normalized maximal voluntary COP excursion (NMVE) calculated as the distance between the point of the vertical projection of the medial malleolus and the average COP position in the inclined posture.

This foot positioning allowed to determine the actual position of the of the vertical projection of the medial malleolus center according to the center of the forceplate in the sagittal plane. It was calculated by deducting 10 cm from the half of the platform length and the sum of the length of the big toe and forefoot (see Fig. 1 for reference). The NMVE was calculated as the distance between the average COP

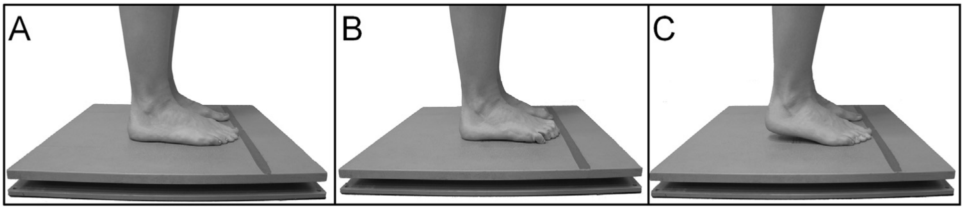

Fig. 2. Three conditions of the feet setup during the LOS test execution; A – flat, B – toes isometric contraction, C – heels raised.

Table 2
The results of intra class correlation (ICC) analysis.

Variable	ICC (3,1)			CI	SEM
	R = 0.75	R = 0.85	R = 0.95		
FFSI [%]	1	1	3	0.77–0.95	2,36
MVE [cm]	1	2	5	0.65–0.92	0,62

Legend: FFSI – forward functional stability indicator.
MVE – maximal voluntary COP excursion.

position in the third phase of the LOS test and the position of the medial malleolus. The calculation of the forward functional stability index FFSI [%] was conducted as follows:

FFSI [%] = NMVE/FFL × 100

where:

NMVE– maximal voluntary COP excursion range calculated from the position of the medial malleolus to the average COP in the third phase of the LOS test corresponding to the maintenance in the inclined position in [cm],

FFL – the length of the forefoot in [cm].

Statistics

The basic parameters of descriptive statistics were calculated. The Shapiro-Wilk's test was used for data distribution assessment. IfThe data were checked for the assumptions of sphericity and uniformity of the variance. When the criteria were met the analysis of variance (ANOVA) for repeated measurements was used. Pairwise contrasts with Bonferroni corrections were used to explore significant effects Significant main effects were tested with Bonferroni's post hoc test. The reliability of the conducted measurements was estimated by the use of intraclass correlation coefficients (ICCs3,1) [10]. Additionally, the Pearson's correlation analysis was used to explore the dependence of the mean

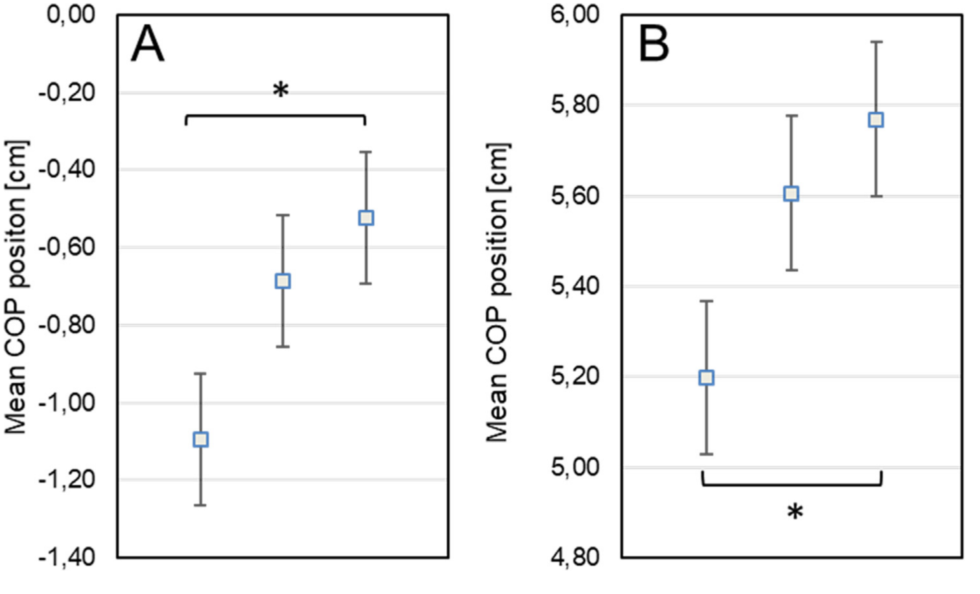

Fig. 3. The COP position (mean ± SD) in the first phase of the LOS test in the consecutive trials with respect to A) the middle of the force plate and B) the center of the medial malleolus.

position of the COP in the first phase of the LOS test with its main outcome which is a maximal voluntary COP excursion. The level of statistical significance was assumed for $P < 0.05$. The Statistica software v.13.1 was used for all the calculations.

Results

Frist, the reliability of the new FFSI was established. The results show the excellent reliability of the FFSI ($R = 0.95$) with only three trials ($CI = 0.77–0.95$, $SEM = 2.36$). The same reliability level can be achieved for the standard MVE with five trials ($CI = 0.65–0.92$, $SEM = 0.62$) (Table 2).

Next, the analysis of the mean COP trajectory in the first phase of the LOS test, during which the subjects were instructed to stand still, was conducted. The anova results showed that there is a significant difference in the mean trajectory of the COP in the first phase between the 1 st and 3rd trial in a series ($n = 30$) ($F(2,58)) = 6.21$, $P < 0.004$, partial $\eta 2 = 0{,}18$) (Fig. 3). The mean trajectory position of the COP in the first phase of the LOS test is also strongly correlated with MVE ($r(28) = -0.62$, $P < 0.05$).

Next, the functional stability limit was tested in the three feet settingstanding conditions. The results of the ANOVA for repeated measures showed a significant main effect of the conditions ($F(2,58) = 46.17$, $P < 0.001$, partial $\eta 2 = 0{,}61$). When the analysis was conducted for men and women together all three conditions significantly differed, the same situation occurred in the men's group only. For women the only significant difference was between the flat foot condition and the two remaining conditions (isometric toes contraction and heel raised) (Fig. 4).

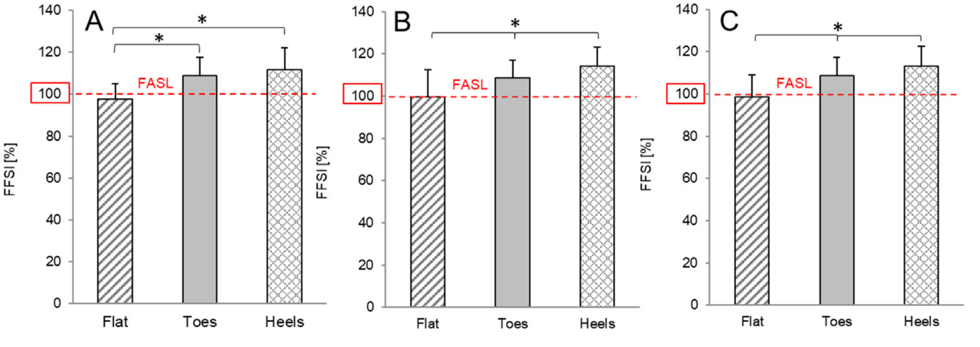

Fig. 4. Forward functional stability indicator (FFSI) in three different feet setup conditions for A) women, B) men and C) women and men together.

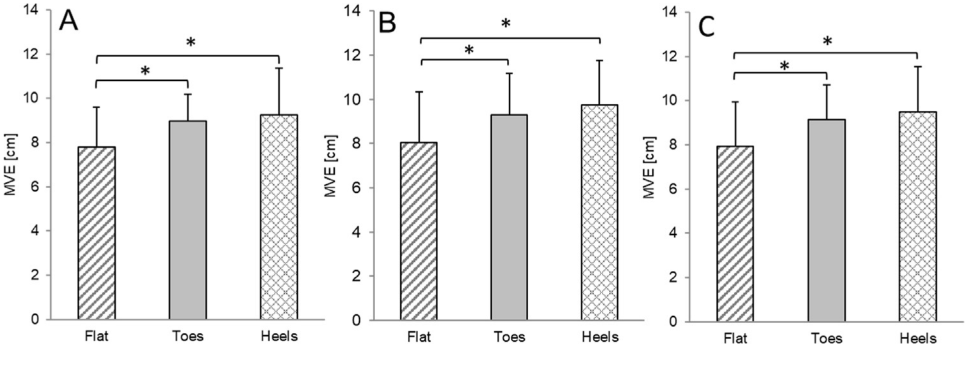

Fig. 5. Maximal voluntary COP excursion (MVE) in different feet setup conditions for A) women, B) men and C) women and men together.

In the flat foot condition the participants were not able to cross the estimated FASL. When the heel raise and the isometric toes contraction were allowed they easily crossed over the FASL (Fig. 4). The modification in foot stance also significantly influenced the MVE, which was the largest for the heel raise condition. Specifically, the isometric contraction and heel raise conditions were significantly different from the flat foot condition ($F(2,58) = 26.99$, $P < 0.001$, partial $\eta 2 = 0{,}48$) in the examined group as well as in men ($F(2,28) = 14.81$, $P < 0.001$, partial $\eta 2 = 0{,}51$) and in women ($F(2,28) = 11.55$, $P < 0.001$, partial $\eta 2 = 0{,}45$) separately (Fig. 5).

Conclusions

Despite numerous studies report experimental data under the same theme of functional stability it is usually impossible to compare these results. Even though it is partly possible when the results are referred to the percent of the BOS, it is still unknown how does it reflect the individual capacity in functional stability – the question whether the person is able to use her or his full potential still remains. This problem is solved with the use of the proposed FFSI, which reflect the actual capacity of the tested persons with respect to their functional stability. With this precise estimate of the individual functional stability limit one should be able to better and faster determine postural control deficits.

Declaration of Competing Interest

The authors report no conflict of interest.

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