The size of the functional base of support decreases with age

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Abstract

Falls occur more often as we age. To identify people at risk of falling, balance analysis requires an accurate base-of-support model. We previously developed a functional base-of-support (fBOS) model for standing young adults and showed that its area is smaller than the footprint area. Our fBOS model is a polygon that contains centre-of-pressure trajectories recorded as standing participants move their bodies in the largest possible loop while keeping their feet flat on the ground. Here we assess how the size of the fBOS changes with age by comparing 38 younger (YA), 14 middle-aged (MA), and 34 older adults (OA). The fBOS area is smaller in older adults: OA area is 58% of the YA area ($p < 0.001$), and 59% of the MA area ($p = 0.001$), with no difference between YA and MA. The reduction in fBOS area among the OA is primarily caused by a reduction in the length of the fBOS. In addition, among older adults smaller fBOS areas correlated with a lower score on the Short Physical Performance Battery (τ=0.28, $p = 0.04$), a reduced walking speed (τ=0.25, $p = 0.04$), and a higher frailty level ($p = 0.09$). So that others can extend our work, we have made our fBOS models available online.

Introduction

Falls are a recurrent problem in the ageing population, with one in every three adults above 65 years of age falling yearly [1]–[3]. Analysing balance is challenging because it is affected by the three-dimensional movements of all of the body's segments and is particularly influenced by foot placement location. Models of dynamic balance, such as the extrapolated center of mass [4] and foot placement estimator [5]–[7], simplify balance analysis by using the position and velocity of the body's segments to calculate the location of a balance point on the floor: if the BOS covers this point the body is considered to be balanced according to the assumptions of the model. The distance between the balance point and the nearest BOS edge (called the margin-of-stability) is often analysed because it provides a measure of how close someone's body is to the boundary that separates being balanced from being off-balance. The accuracy of the margin-of-stability depends on both the balance model and the BOS model.

Unfortunately, there is no standardised definition of the geometry of the BOS. Many balance studies rely on an ad-hoc definition for the nearest BOS edge when evaluating the margin-of-stability, often using either just a single toe or heel motion capture marker [8]. This approach assumes that the BOS is the same as the footprint, but evidence shows that the area that can functionally support a large fraction of the body's weight is much smaller [9], [10]. Our previous work [10] suggests that using the footprint as the BOS can introduce 2.3-5.0 cm of error into the margin-of-stability for an average-sized adult foot. Although this may seem small, it is large in comparison to the dimensions of the fBOS and can mean the difference between remaining stably balanced and needing to take a compensatory step.

While the fBOS has been measured in a number of studies, the two-dimensional shape of the fBOS from a single foot has not been measured in older adults. King et al. [11] and Tomita et al. [12] measured the extent of the fBOS in a series of discrete directions under both feet of younger and older adults and found that the fBOS is smaller in

older adults. Since ground forces were measured under both feet using a single force plate, it is unfortunately not possible to construct an individual foot's fBOS from their measurements. Hof and Curtze [13] measured the effective BOS (eBOS) in the sagittal and frontal planes by perturbing standing participants and using a model to infer the margin-of-stability from their resulting movements. While the latter methodology makes it possible to capture the eBOS during a perturbation response, the two directions analysed in their work are insufficient to create a two-dimensional eBOS model of each foot. Melzer et al. [14] compared the COP area between younger and older adults during quiet standing both with and without a distraction task. Although the results showed a greater sway in older adults, the task did not challenge participants' balance sufficiently to extract the fBOS. The studies that compare younger and older adults [11], [12], [14] make it clear that there are noticeable differences between the two groups, suggesting that an age-specific fBOS model is needed.

In this work, we examine how the two-dimensional fBOS area varies across 38 younger adults (YA), 14 middle-aged adults (MA), and 34 older adults (OA). Similar to our previous fBOS model of younger adults, we define the fBOS as the convex polygon that encloses the area on the bottom of the foot that can support at least 40% of the body's weight [10]. In contrast to previous studies that had participants lean in discrete directions [9], [11], [15] we obtain continuous measurements of the fBOS by asking participants to move their body's center of mass in large, slow, circular movements to generate maximum-voluntary-COP excursions while keeping the feet flat on the ground. In addition, we measure frailty level, physical performance, and fear of falling to see if any age-related reduction in fBOS area correlates with these commonly measured mobility metrics. Finally, as studies so far focused solely on standing, we measure COP path during walking to see if this correlates with the fBOS length during standing. As might be expected, we hypothesize that the fBOS area declines with increasing age, decreasing physical performance, increasing frailty level and a shorter COP path during walking.

Methods

Groups of older, middle-aged and young participants were recruited and assessed at Heidelberg University. Participants were excluded if they had neurological, cardiovascular, metabolic, visual, auditory, mental or psychiatric impairments or injuries that might interfere with the planned task; or were unable to independently walk short distances or stand up from a chair. Younger participants had to be between 17-39 years of age, middle-aged participants between 40-65 years of age, and older participants 65 years or older. Older participants were excluded if their frailty level was more than moderately frail on the Clinical Frailty Scale (score$\geq$6) [16], or if they were severely cognitively impaired (Mini-Mental State Examination score$\leq$ 17) [17], [18]. The protocol was approved by the IRB of the medical faculty of Heidelberg University. All experiments were performed in accordance with local guidelines and the Declaration of Helsinki. Participants provided written informed consent.

The 34 older adults (22 females) included 20 with right-side foot preference (76$\pm$6 [66 to 89] yr, 25 $\pm$ 4 [17-33] kg/m^2). The frailty level of the older group ranged from very fit to vulnerable on the Clinical Frailty Scale (7 adults of level 1; 13 adults of level 2; 10 adults of level 3 and 4 adults of level 4) [16]. The 14 middle-aged adults (6 females) included 6 adults with right-side foot preference (50$\pm$7 [41-63] yr, 24 $\pm$ 3 [20-31] kg/m^2). The 38 young adults (16 females) included 20 adults with right-side foot preference (26$\pm$5 [21-39] yr, 23 $\pm$ 3 [18-30] kg/m^2).

0.1 Protocol

The measurements and data analysis are similar to the bipedal standing fBOS assessment of our previous study of young adults [10]. Participants wore sports or comfortable shoes that left their ankles uncovered. They stood with feet hip-width apart, toes forward, and with each foot on a force plate. Participants were instructed to move their center-of-mass as much as possible in forward, outwards, backwards, and inward directions in slow, circular movements, while trying not to move their feet or lift their toes or heels. No instructions were given for arm movements or position, or how to best lean in the different directions. If a participant was not effectively moving their COP, they were given examples by the examiner and encouraged to try again. Participants were given as much time as needed and encouraged to make plenty of circular movements. If participants lost their balance the trial was repeated. Participants were not secured in a safety harness as it could affect the assessments, but were spotted by a nearby examiner.

Full body and foot movement was recorded at 150 Hz using a motion capture system (Qualisys, type 5+ cameras, Gothenburg, Sweden) and ground reaction forces at 900 Hz using two ground-embedded force plates (Bertec, Columbus, OH, USA). Motion capture markers (14mm) were placed using a small adjustment for the feet of the full-body IOR marker model: on the heel, medial and lateral ankle epicondyle, the lateral outside of the MTP5 metatarsal, the medial outside of the MTP1 and the front

tip of the longest toe (see Figure 2 in [10]). Marker data were labeled in Qualisys.

We also collected data to assess the frailty, physical performance, and fear of falling in our older participants. We used the the score on the Clinical Frailty Scale [16] to assess the frailty level, the total score (and timing on the individual items) on the Short Physical Performance Battery (SPPB) [19] to assess physical performance, and the score on the short Falls Efficacy Scale International to assess fear of falling (FES-I; [20]). These metrics were not measured from the younger and middle-aged adults because these age groups typically saturate each of these measures.

To understand how the fBOS area measured during bipedal flatfoot standing relates to the COP path during walking, standard gait analyses were performed at comfortable walking speed. Participants walked for several trials up and down the lab while ground reaction forces were measured with the two ground-embedded force plates and kinematics using the motion capture system. Qualisys software calculated the COP data from the ground reaction forces. Strides with good full single-foot landing on the force plate were selected by visually inspecting the foot landing in Qualysis as well as checking the force data in MATLAB. Good strides were available for n=32 older adults (n=18 of frailty level 1 or 2, n=10 frailty level 3 and n=4 of frailty level 4). To exclude data outliers, force and COP data were taken above a threshold of 50N vertical force. The foot-normalised COP path length was calculated by taking the maximum minus the minimum COP points in the anterior-posterior direction in the instructed direction of travel, and dividing these by the foot length calculated from the motion capture markers as above. The medio-lateral direction was not assessed because the COP typically does not traverse the width of the foot during walking.

0.2 Functional Base-of-Support

Older adults found the experimental fBOS task particularly challenging: widely circle the COP without moving the feet. As a result, we had to have a detailed set of criteria to identify COP data in which the participant's foot could be considered to be flat on the ground. Specifically, we selected COP data that had at least 150 consecutive data points (1 second long), supported least 40% of body weight on the respective force plate (which was the main reason for data point exclusion), during which the foot was sufficiently flat on the ground, while excluding the largest 0.1% COP transitions (see [10] for more details). The resulting force plate data was low-pass filtered and down-sampled to match the sampling frequency of the marker data. All filtering was done using a zero-phase second-order low-pass Butterworth filter with a cutoff frequency of half the sampling rate of the marker data.

The fBOS of each participant and each age group were evaluated using the processed COP data. First, we projected the COP data onto a foot-fixed frame that is coincident to the footprint during quiet standing. Next, we computed the fBOS of each foot as the polygon that represents the convex-hull that surrounds the COP data for each foot. We reflected the right foot fBOS polygon medio-laterally (making it equivalent to the left foot) and averaged the convex hull of the left and reflected right feet together. Finally, each participant's fBOS was normalised by length and width before the average fBOS was computed for each age group using the arc-length indexed polygon averaging method described in Appendix C of [10]. All calculations were performed using custom-written scripts in Matlab (version 2021a, Natick, MA, USA). Our age-specific fBOS models and functions to convert them to different marker sets are available online (see the *Data Availability Statement* for details).

0.3 Statistics

We compare the normalised fBOS area and dimensions across the age groups. The normalised fBOS area is the primary outcome and it is the area of the fBOS scaled by the area of the footprint. In this work, the area of the footprint is the area enclosed by the six markers on each foot. Our secondary outcome variables describe the shape of the fBOS, including the inward distance from the heel, front toe, lateral ankle and little toe markers, and the fBOS length and width normalised to the individual foot size. Statistical analyses were performed in Matlab (version 2021a, Natick, MA, USA).

Differences in primary and secondary variables between the three age groups were assessed using a Kruskal-Wallis test, as the data in the individual groups did not appear normally distributed when plotted in histograms. Posthoc comparisons were performed on mean rank values using Matlab's *multcompare* function. To see how the normalised fBOS area declined with biological age in detail, it was correlated to the merged data from the three groups using Spearman's correlation.

To gain further insight into the meaning of different fBOS sizes in the older adults, we compared the normalised fBOS area to other related metrics. First, using a Kruskal-Wallis test we compared the fBOS size across the three frailty groups: level 1 and 2 were merged as they are more difficult to discriminate (n=20); level 3 (n=10) and level 4 (n=4) on the Clinical Frailty Scale (score$\geq$6) [16]) were left as separate groups. Next, we examined the relation to physical performance by correlating the nor-

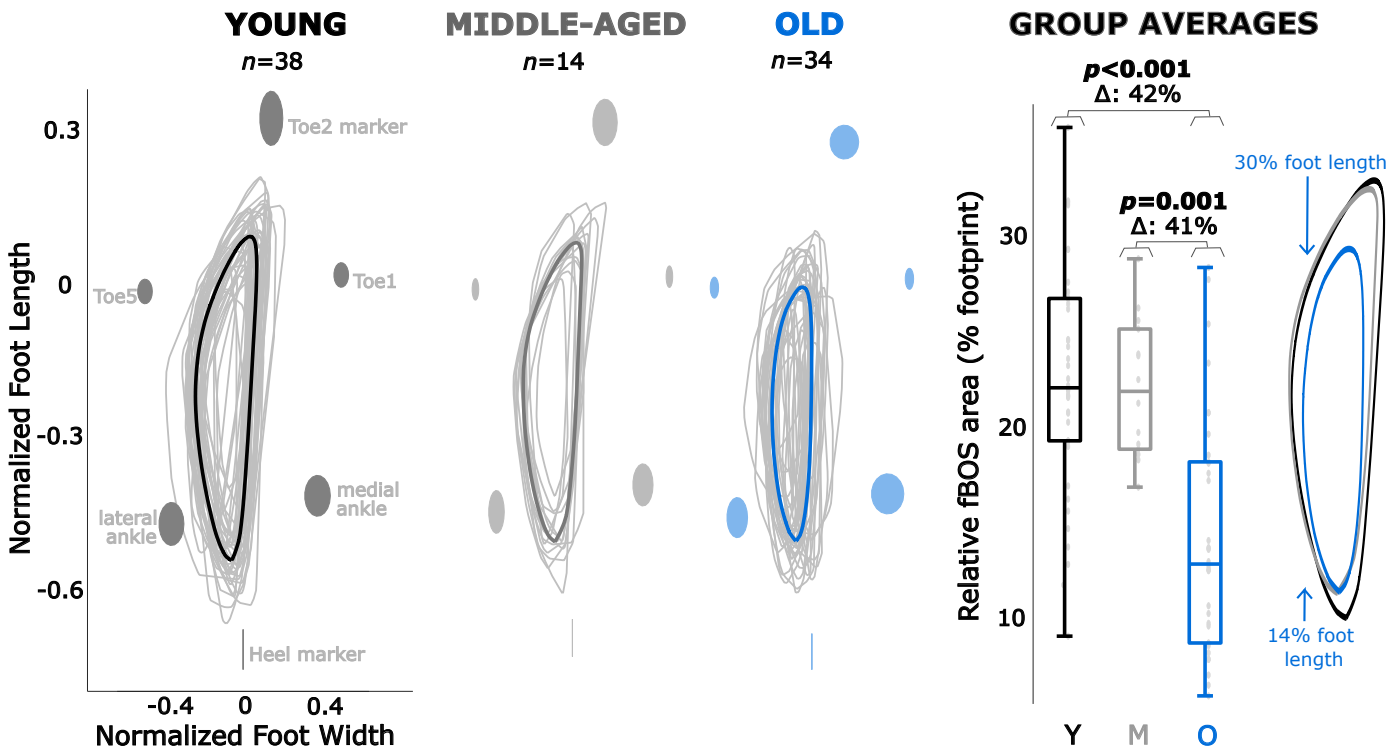

Figure 1: **Functional base of support (fBOS) area per age group.** Areas are normalised to an individual's foot length and foot width, with group averages shown in bold. The ellipses show the standard deviation of the marker positions across the group. Note that the heel marker has no mediolateral deviations because the y-axis of the fBOS passes through the heel marker [10]. The boxplots indicate the median and interquartile ranges of the area surface per group, with individual participant's values indicated with gray dots and outliers with a red cross. The average profiles of the fBOS areas are shown on the right for comparison. Significant differences are indicated with the p-value.

malised fBOS area to the Short Physical Performance Battery score (SPPB)[19], as well as the 4m gait speed and sit-to-stand-to-sit time taken as part of the SPPB, using Kendall correlations. Similarly, we explored the correlation to fear of falling using the score on the Falls Efficacy Scale [20]. Finally, we evaluated the correlation between the bipedal standing foot-normalised fBOS length and the dynamic foot-normalised COP path length during walking across 32 older adults (see section 0.1) using a Spearman correlation.

Results

The average fBOS was much smaller than the anatomical outline formed by the foot markers: the median and range were only 22 [9-36]% of the footprint for the young group, 22 [17-29]% for the middle-aged group and 13 [6-28]% for the older group. The fBOS area is longer than it is wide: the maximum fBOS length normalised to foot length was 65 [49-81]% for young, 61 [50-65]% for middle-aged and 53 [22-72]% for older participants. The maximum fBOS width normalised to foot width was 35 [21-62]% for young, 35 [24-39]% for middle-aged and 21 [12-40]% for older participants. Note the large variability between adults within each group.

The fBOS area decreased with age ($p<0.001$): the older group's median fBOS area was only 58% of the size of the young group ($p<0.001$) and 59% of the size of the middle-aged group ($p=0.001$; Fig. 1). The individual data points across all age groups also show that the fBOS area correlated to age (Spearman $\rho=-0.52$, $p<0.0001$; Fig. 2). This age-related reduction in fBOS area is direction-dependent: while the inward distances from the lateral ankle ($p=0.27$) and little toe ($p=0.89$) do not change, the fBOS edge retreats inwards the foot away from the toes ($p=0.0006$) and heel ($p<0.015$). Specifically, the inward normalised distance from the toes increases from 21 [10-36]% in young ($p=0.0008$) and 21 [16-30] % in middle-aged ($p=0.025$) to 28 [16-43]% of the foot length in older adults. The inward distance from the heel increases from 17 [9-29]% in young ($p<0.01$) to 20 [13-39]% of the foot length in older adults (with 18 [14-28]%, $p=0.30$, in middle-aged).

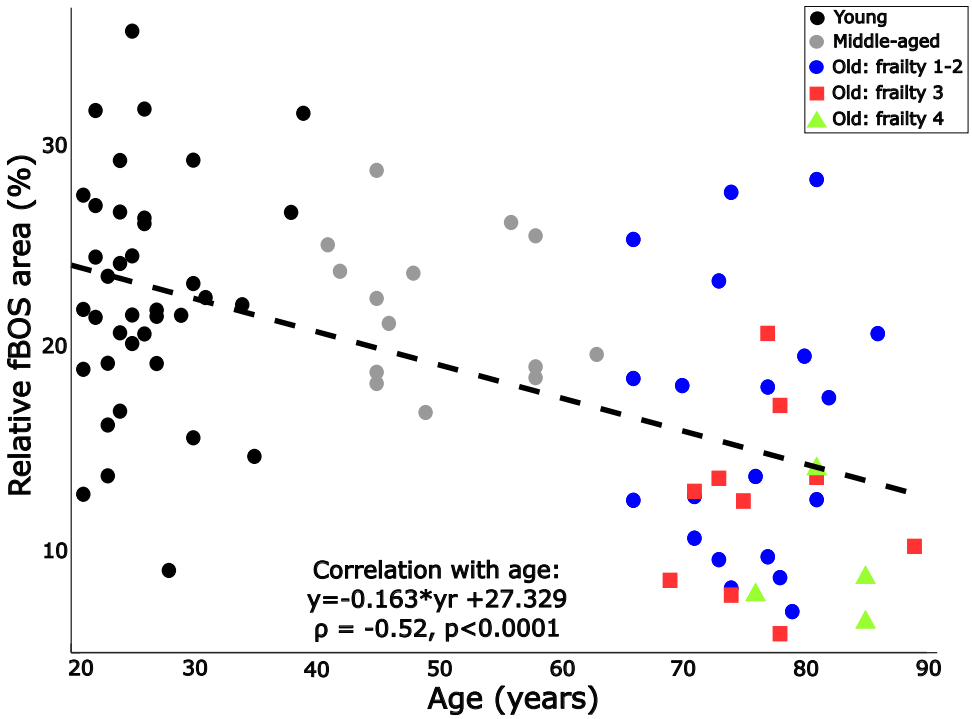

Figure 2: **Change in the functional base of support (fBOS) area with biological age.** The young adults are shown in black, the middle-aged in grey, and the older adults in colour. While not separately examined here, frailty levels 1 and 2 are shown in red squares, level 3 in blue circles and level 4 in green triangles for context. The relationship was examined using a Spearman correlation (the p-value and ρ-value are given, as well as the least-squares first-order linear fit.

In addition to ageing, the size of the fBOS area appears to also be related to frailty and physical performance. The fBOS area tended to be smaller in older adults with a higher level of frailty (p=0.09; Fig. 3A), despite a small sample size in this group. The median fBOS area of the pre-frail adults (frailty level 3) was 81% of the non-frail people (level 1 and 2; p=0.54), while the fBOS area of mildly frail adults (level 4) was only 53% of the non-frail people (p=0.10). A decrease in physical performance was weakly correlated with a decrease in fBOS area, both in terms of the total SPPB score (τ=0.28, p=0.04; Fig. 3D) as well as the 4m gait speed (τ=0.25, p=0.04; Fig. 3B). There was no correlation between fBOS area and SPPB sit-to-stand time (also when removing the lowest outlier) or fear of falling (FES; Fig. 3C, E). The normalised COP path length during walking increased with normalised fBOS length (ρ=0.49, p=0.004; Fig. 4).

Discussion

Injury due to falling is common and on the rise among older adults [1]–[3]. Model-based balance analysis using the margin-of-stability has the potential to identify people who are at risk of falling before injury occurs, but requires an accurate fBOS model. In this work, we extended our prior fBOS study of younger adults [10] by making measurements and age-specific geometrical models across a large sample of younger adults, middle-aged adults, and older adults.

We found that the area of the single foot fBOS was much smaller, only 22%, of the area of the footprint across all age groups. This is similar to our prior work with younger adults [10], but smaller than the 47% reported previously [12] across two feet. Note that the footprint based on just six foot markers is a slight under-representation of the physical footprint. In addition, we also found that the length of the fBOS in the anterior-posterior direction is 65% of the length of the foot, which is similar to the 50-60% range of prior work [11], [21], [22]. Regardless of age, the fBOS is thus smaller than the area of the footprint.

As hypothesized, we found that age does reduce the fBOS of older adults, but our hypothesis did not apply to middle-aged adults who showed no reduction in fBOS area with age. We found that the whole fBOS area declines from 22% of the footprint area in younger adults to only 13% of the footprint area in older adults, a result that is in

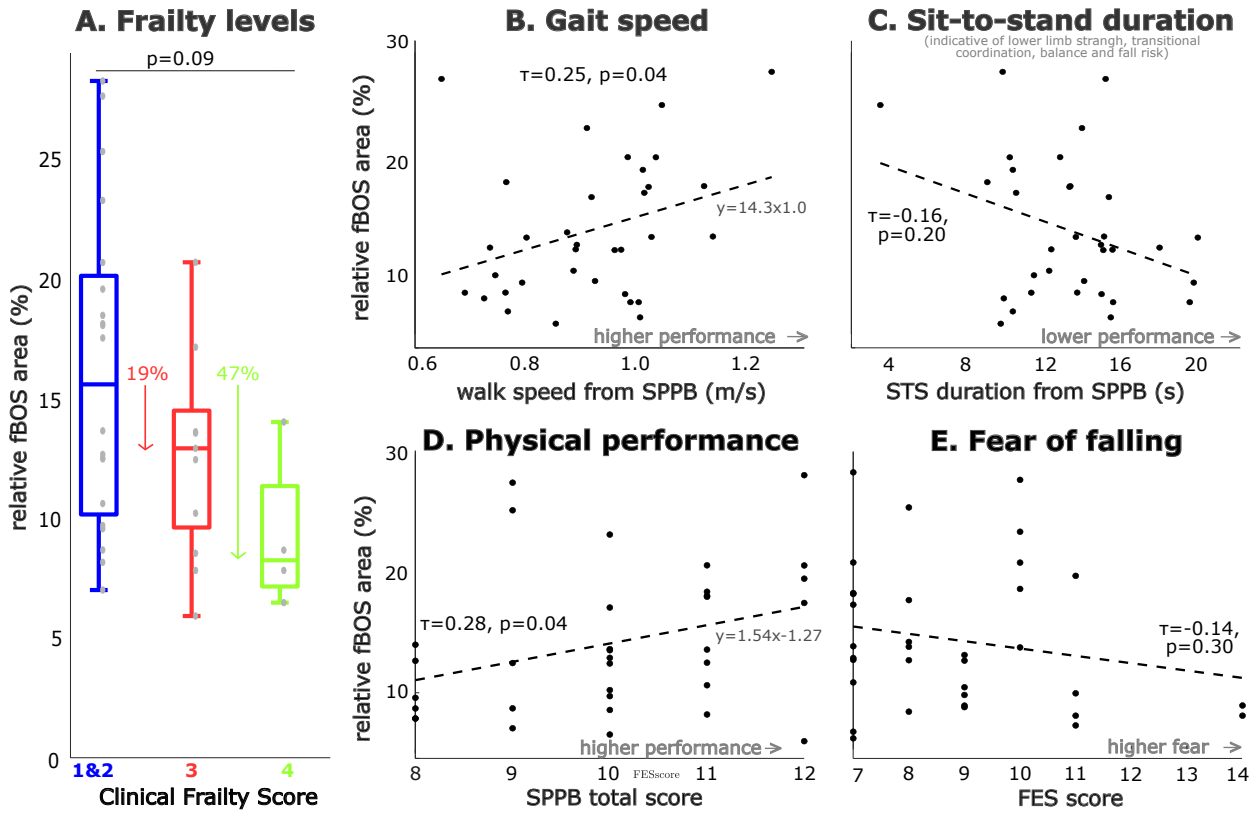

Figure 3: **Relation between frailty level, physical performance and fear of falling in older adults versus the functional base of support (fBOS).** The relationship of the normalised fBOS area to the foot outline relative to frailty level is shown (A), with frailty based on the Clinical Frailty Scale and with 1 and 2 merged. The percentage decrease for frailty levels 3 and 4 is given relative to the median value of levels of 1 and 2 and includes the level 3 outlier (the reduction is 28% without the outlier). Physical ability was examined as the total Short Physical Performance Scale (SPPB) score (D), the underlying 4m gait speed test (B) and the 5 times sit-to-stand time (C). Fear of falling was established using the Short Falls Efficacy Scale (E). Relationships were examined using Kendall correlations and the least-squares first-order fit to the data points is shown for reference.

line with previous fBOS studies of older adults [11], [12], [21]–[26]. The reduction, we found, is not uniform but is most pronounced at the toes and heel, with no differences at the sides of the foot. Tomita et al. [12] also found the largest decrease at the toes, followed by the heel, but also found a decrease at the side. While we aimed to include more older and frail persons, a larger group of middle-aged participants should be measured to identify the general age of onset of fBOS decline.

We found a considerable variability between participants, with some older participants displaying values larger than some younger participants, as has been noted before for discrete limits of stability [11], [12]. Even for the young, the fBOS areas range from 9 to 36%, with the middle-aged and older adults showing a similarly large spread in values (between 3-29%). As the task required to measure the fBOS is challenging, these differences may arise due to differences in physical performance (strength [27]–[29]), coordination [23]–[25], sensory acuity [30]–[32], or perhaps due to the structure of the foot (flexible or stiff feet, ankle joint laxity) rather than a difference in balance ability.

Biological age might not be the best predictor of fBOS area decline, which motivated us to measure clinically relevant mobility metrics. As hypothesized, the fBOS area decreased with both the clinical SPPB test of physical performance and comfortable walking speed, a shorter COP path during walking and tended to decrease with increasing frailty level. Particularly, the relation with walking speed is interesting, as walking speed is considered a functional vital sign and predictive of mental health, disability, falls, physical activity and more [33], [34]. We did not find a correlation with fear of falling using the FES scale, which is in contrast Binda et al. [27] who found a correlation between anterior-posterior limits and scores on the Activities-specific Balance Confidence (ABC) scale. It is

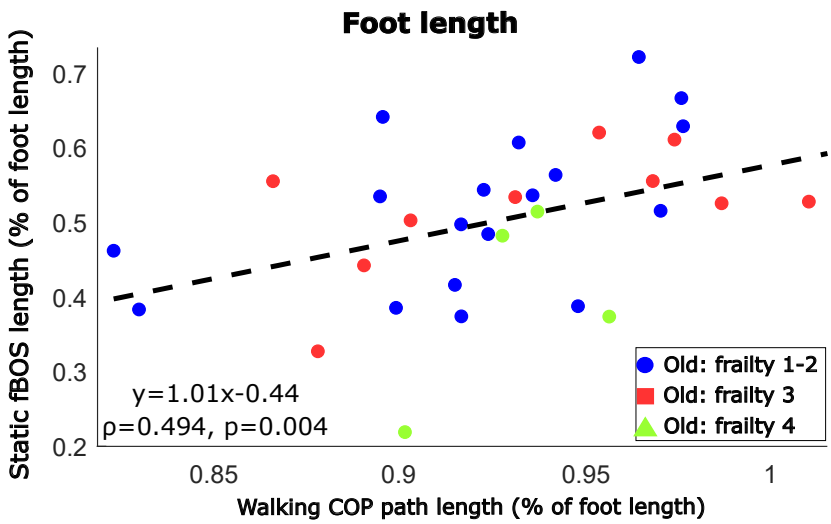

Figure 4: **Relation between standing and walking: the standing functional base of support (fBOS) length versus the center of pressure (COP) path length during walking in older adults.** The least-squares first-order fit to the data points and the results of the Spearman correlation are given. The colour-coding of the different frailty levels is solely for context.

worth noting that Binda et al. [27] specifically recruited people who had a fear of falling, and we did not. A relation between fBOS anterior-posterior limits versus fall history and balance recovery has been reported [15], [21], [35]. Unfortunately, we could not investigate such relations using the fBOS area as only a few individuals were fallers or had a low balance score. The relation between standing fBOS length and walking COP trajectory length is the first step in validating and measuring the fBOS area during dynamic movements such as walking.

Our results may be limited by the task we used to measure the fBOS, group size, and the footwear worn by participants. First, we can never be sure participants reached their boundaries during the whole circular motion, though compensatory arm movements made it clear that many found the task challenging. As a result, differences in motivation, fear of falling, and adherence to instructions could have enlarged the variability in fBOS area between participants. Next, while our group size should be sufficient for the main comparisons between age groups, more older and particularly frail adults would have improved the power of the correlation and secondary analyses. It should be noted that one participant (72 yrs, frailty level 2) was not included in the population due to an abnormally large fBOS area that we think is related to inappropriate thresholds for foot movement for this participant (see details in [10]). Finally, we did not control for footwear since we did not find any systematic differences between barefoot and shod fBOS areas in our prior study of younger adults [10]. However, since we did not examine different types of footwear in our prior work, it is possible that the fBOS is affected by the insole stiffness or orthopaedic shoes that are often worn by older adults (this was not recorded).

In this work, we have measured the shape of the fBOS of a single foot across younger, middle-aged, and older adults, to be able to apply our model to walking with single-stance phases. We have chosen to describe the fBOS as a two-dimensional polygon [10] because this shape makes it possible to accurately assess the margin-of-stability in any direction, rather than be limited to the specific measurement directions of prior work. We averaged over the left and right foot, as we previously did not find an effect of dominant leg in young persons [10] though further analysis using only the smallest of the left and right fBOS areas resulted in a similar correlation to age (ρ=0.47, p<0.001). Our measurements in younger, middle-aged, and older adults make it possible to scale an age-specific fBOS template to a participant to evaluate the margin-of-stability more accurately than would be possible otherwise. Our fBOS models offer far better accuracy than using motion capture markers to directly define the BOS. In younger adults, our fBOS model will improve the accuracy of the margin-of-stability by 6.5 cm from the toes, 5.2 cm from the heel, and 2.0 cm from the side (at the height of TMP5), for an average-sized foot of 30 cm by 10 cm. When the age-specific fBOS model is applied to older adults the improvements in accuracy increase to 8.3 cm at the toes and 6.5 cm at the heel. These improvements in accuracy are large in comparison to the size of the foot and will make it easier to detect people who have balance problems before

injury occurs. The provided age-specific models (applicable to the IOR [36] or PlugInGait [37], [38]) marker sets with code to convert to other marker models) thus offer a generally applicable definition for the fBOS which can be applied to foot marker data recorded during different movements to analyse balance.

Conclusion

We measured the functional base of support across younger, middle-aged and older adults and found that this fBOS area decreases with age. In addition, we found that the fBOS area correlates with reduced functional and walking abilities. During walking, the length of the fBOS also correlates with the length of the COP trajectory in the direction of travel. So that others can extend our work and apply it to their own research, we have made the fBOS models and example data available online (see the *Data Availability Statement* for details).

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Author Contributions

LHS and MM designed the experiment; LHS and TG were responsible for participant recruitment, data collection and data processing; MM and LHS created the fBOS code and analysis pipeline respectively; LHS and MM analyzed and interpreted the data; LHS and MM wrote the manuscript and generated the figures; TG, KM and MM, provided critical feedback on the data interpretation and manuscript. KM and LHS obtained funding for the work.

Data Availability Statement

The outcome variables for all individuals that are used for statistical analysis are made available in the supplementary material file *SupMat_individuals_datavalues_v1.xlsx*. The raw data files are available from the corresponding authors on reasonable request. The fBOS models, functions to calculate the fBOS model from data, convert fBOS models to different marker sets, and to average fBOS convex hulls, as well as example data to use these functions, are shared at GitHub: `https://github.com/mjhmilla/functionalBaseOfSupport`.

License Statement

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Additional Information

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Figure Legends

Fig. 1: Functional base of support (fBOS) area per age group. Areas are normalised to an individual's foot length and foot width, with group averages shown in bold. The ellipses show the standard deviation of the marker positions across the group. Note that the heel marker has no mediolateral deviations because the y-axis of the fBOS passes through the heel marker [10]. The boxplots indicate the median and interquartile ranges of the area surface per group, with individual participant's values indicated with gray dots and outliers with a red cross. The average profiles of the fBOS areas are shown on the right for comparison. Significant differences are indicated with the p-value.

Fig. 2: Change in the functional base of support (fBOS) area with biological age. The young adults are shown in black, the middle-aged in grey, and the older adults in colour. While not separately examined here, frailty levels 1 and 2 are shown in red squares, level 3 in blue circles and level 4 in green triangles for context. The relationship was examined using a Spearman correlation (the p-value and ρ-value are given, as well as the least-squares first-order linear fit.

Fig. 3: Relation between frailty level, physical performance and fear of falling in older adults versus the functional base of support (fBOS). The relationship of the normalised fBOS area to the foot outline relative to frailty level is shown (A), with frailty based on the Clinical Frailty Scale and with 1 and 2 merged. The percentage decrease for frailty levels 3 and 4 is given relative to the median value of levels of 1 and 2 and includes the level 3 outlier (the reduction is 28% without the outlier). Physical ability was examined as the total Short Physical Performance Scale (SPPB) score (D), the underlying 4m gait speed test (B) and the 5 times sit-to-stand time (C). Fear of falling was established using the Short Falls Efficacy Scale (E). Relationships were examined using Kendall correlations and the least-squares first-order fit to the data points is shown for reference.

Fig. 4: Relation between standing and walking: the standing functional base of support (fBOS) length versus the center of pressure (COP) path length during walking in older adults. The least-squares first-order fit to the data points and the results of the Spearman correlation are given. The colour-coding of the different frailty levels is solely for context.