Effects of Age and Gender on Toe Flexor Muscle Strength

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Background. Toe flexor muscle strength determines the anterior limit of the functional base of support, thereby affecting a standing individual’s maximum forward reach or lean capacity. We developed a method for measuring toe flexor muscle strength in order to test the null hypotheses that it is neither affected by age nor gender.

Methods. Gender-balanced groups of 20 healthy young adults (YA) (average age 22.8 years) and 20 healthy older adults (OA) (average age 73.2 years) participated in the study. Toe flexor isometric muscle strength, calculated as the maximum volitional moment developed simultaneously in the sagittal plane by the toe flexor muscles about a reference axis through the first metatarsophalangeal joint, was measured in three trials while subjects reached forward as far as possible while standing on a force plate.

Results. Significant age (p < .005) and gender (p < .0005) differences were found in maximum toe flexor muscle strength. OA were 28.9% less strong than the YA [mean (SD) 13.5 (5.7) Nm and 19.0 (6.8) Nm, respectively]. The men developed 39.1% greater strength than the women [20.2 (7.1) Nm and 12.3 (3.7) Nm, respectively]. However, when normalized by body size (body weight × height), the gender difference in strength no longer reached statistical significance. Across all subjects, the anterior limit of the functional base of support was significantly correlated with toe flexor strength (coefficient of determination: 0.84).

Conclusions. Toe flexor muscle strength decreased significantly with age. This decrement underlies the known age-related reduction in the functional base of support.
A vertically oriented 11-cm by 6-cm finger touch plate, mounted on a 400 N capacity transducer measuring horizontal force, was rigidly mounted in the midsagittal plane at shoulder height. This provided a target for the subject to reach toward and push against with his or her fingertips in order to restore balance, should he or she overreach (Figure 1), but also allowed us to verify the absence of tactile contact during the short interval when toe flexor strength data were collected.

Real-time knowledge of results concerning the maximum value of the equivalent toe flexor muscle moment that the subject developed was provided using two forms of real-time visual feedback: an oscilloscope trace and a peak detector with a digital readout. When subjects moved their centers of reaction forward, the horizontal oscilloscope trace was arranged to translate vertically. Subjects were instructed to attempt to “move that line as far up as possible” on each trial. The peak detector stored and displayed for the subject the maximum strength value on a digital display. The six channels of force plate data and the touch plate force were recorded at 100 Hz using a 12-bit analog-to-digital converter and microprocessor.

Subjects performed all tests without shoes or socks. The foot used to begin testing was randomly selected. The subject was asked to stand with the test foot on the edge of the force plate and the other leg on a block of wood the same height as the force plate. The center of the first MTJ was placed over the x-axis of the force plate with the longitudinal foot axis (line joining center of second MTJ to calcaneal midline) normal to that line (Figure 1). Foam padding was placed on the force plate around their heels and toes in order to standardize foot position relative to the center of the force plate. The subject was then instructed to place all his or her weight on the test leg and, using the oscilloscope for feedback, to try to move his or her center of ground reaction force as far forward as possible, holding that position for only 1 to 2 seconds (Figure 1). The subject was allowed to flex the stance knee slightly, if he or she so wished. The contralateral arm was to be kept at the side throughout the experiment, while the ipsilateral arm was used to reach forward toward the transducer and, if necessary, was used to regain their balance. The subject was told to keep the contralateral foot at the malleolar height of the stance foot without touching it. Each subject was allowed to practice three times on his or her test foot. Then, three trials were performed on the test foot, after which three trials were performed on the contralateral foot. Each subject rested for approximately 20 seconds between each trial and 1 minute between tests on each foot.

A spotter stood behind the subject’s shoulder throughout the experiment. The spotter was responsible for the subject’s safety, ensuring that he or she kept his or her feet in the correct position and watching to ensure he or she performed the experiment correctly.

### Data Analysis

The force plate data were low-pass filtered forward and backward (MATLAB®, 2nd order Butterworth) with a cutoff frequency of 10 Hz. The equivalent maximum isometric toe flexor strength, S, was measured from the maximum quasi-static moment that was exerted about the midline (x-axis) of the force plate during the 1 to 2 seconds when the vertical ground reaction force equaled body weight ± 2%. S is thus the total flexor muscle moment developed in the sagittal plane by all applicable toe flexor muscles about a reference axis in the frontal plane through the center of the first MTJ. In effect, it is the maximum toe flexor muscle strength that would act on an equivalent hallux of length D, where D is the anatomic distance in the sagittal plane from the MTJ to the distal end of the longest toe (Figure 1). L, the functional toe length, was calculated by dividing S by the net vertical ground reaction force, R, both measured using the force plate. Thus, L is the maximum distance (in mm) that the subject could move the center of ground reaction force (R) forward of the first MTJ. The percentage functional toe length was calculated as L divided by D and multiplied by 100 (Figure 1).

Finally, in order to facilitate intersubject comparisons, the maximum toe flexor strengths (in Nm) were normalized with respect to one of three alternative measures of body size: body weight times maximum toe length; body weight times maximum foot length; and, finally, body weight times body height (10). Final selection of the normalization parameter was made by choosing the measure, the product of body weight times body height, demonstrating the highest linear correlation coefficient between body size and toe flexor strength.

### Statistical Analysis

Analysis of variance (ANOVA) was used to test the null hypotheses that toe flexor strength does not differ significantly between the young and old and/or male and female groups. An analysis of covariance (ANCOVA), with covariates of foot length, foot width, toe length, and dominance of foot, was also performed on the absolute and normalized toe flexor strengths. Posthoc, two-sided, t tests were used in order to determine the direction of age and gender differences in maximum toe flexor strength. In addition, two-sided, paired t tests were performed to assess day-to-day repeat-
ability and to examine whether there were any significant differences in dominant and nondominant toe strengths. *P* values less than .05 were considered statistically significant.

**RESULTS**

**Maximum Toe Flexor Strength**

There were no bilateral differences in the absolute maximum toe flexor strengths for any of the four groups (Table 2) (*p* = .228). Therefore, the subsequent analyses focus only on the dominant foot data.

In testing the primary hypotheses, significant age (ANOVA, *p* = .001) and gender (ANOVA, *p* < .0005) differences in absolute toe strength were found. There was neither a difference in the interaction between age and gender (ANOVA, *p* = .090), nor were there differences in the covariates (ANCOVA, *p* > .05). The YA had 28.9% higher absolute toe flexor strength than the OA (*p* = .008). Men had 39.1% greater absolute toe strength than the women (*p* < .0005).

A significant age (ANOVA, *p* = .002) difference was found in normalized toe strength: YA had 26.8% greater normalized toe flexor strength than the OA (Figure 2). There was, however, no gender difference in normalized toe strength (ANOVA, *p* = .076). Finally, there was neither a difference in the age by gender interaction (ANOVA, *p* = .606), nor differences in the covariates (ANCOVA, *p* > .05).
The percentage functional toe length of the YW and YM (35.0% and 40.6%, respectively) showed that these young subjects used significantly more \((p < 0.001)\) of their toe length to contribute to their functional base of support than did the OW and OM (25.4% and 28.1%, respectively). Figure 3 shows the significant association \((R^2 = 0.8405)\) between S and L.

We found that normalizing absolute toe strength by the product of body weight times height resulted in a smaller coefficient of variation than did the other candidate normalization schemes. When all subjects were included, the correlation between toe flexor strength and the product of body weight times height resulted in a coefficient of determination \((R^2)\) of 0.3726 (Figure 2). The regression line for the young subjects suggests that toe flexor strength is approximately 1.68% of the product of body weight (in N) times height (in m) minus 1.252. For the older subjects, the regression analysis suggests that toe flexor strength is 1.49% of the product of body weight times height minus 3.832.

Repeatability

The coefficient of variation of the difference in toe flexor strength between the first and second days in three YW was 10.1%.

DISCUSSION

We present a method for measuring functional toe flexor strength in the standing posture. Using this method, we have obtained the first estimates of the effect of age and gender on toe flexor strength in healthy adults. The age-related reduction in maximum equivalent flexor moment about the first MTJ was significant in these healthy subjects, whether measured in units of absolute strength (Nm) or when that strength was normalized by a measure of body size. Although impairments in ankle strength, coordination, or one legged-balance, and even fear of falling could conceivably underlie these age differences in measured toe strength, we consider their effects on measured toe strength negligible in these screened healthy elderly. This argument is supported by the similarity of the group variances here, as well as at the ankle in similar subject groups (11).

When standing individuals initiate a forward reach, they generate forward angular and linear momentum of their body. To arrest this momentum before it carries their center of gravity beyond their FBOS (for example, 12), they typically use the plantarflexor muscles to depress the metatarsophalangeal joints against the ground, thereby moving the center of ground reaction force \((R)\) toward the MTJ. Hence, if their center of gravity reaches their MTJ with forward momentum, then they can only arrest it by moving \(R\) anterior to the MTJ by using toe flexor muscle strength. The greater their strength, the more the subjects can increase the reaction force under the distal phalanx of each toe, especially the long toes, and the further they can move \(R\) ante-

### Table 2. Mean (SD) Absolute and Normalized (“Norm”) Toe Flexor Strength* by Group

<table>
<thead>
<tr>
<th>Foot</th>
<th>Women</th>
<th>Men</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Young</td>
<td>Older</td>
</tr>
<tr>
<td>DF [Nm]**</td>
<td>13.8 (3.5)</td>
<td>10.8 (3.3)</td>
</tr>
<tr>
<td>NDF [Nm]</td>
<td>14.0 (5.0)</td>
<td>10.2 (5.5)</td>
</tr>
<tr>
<td>Norm DF†‡</td>
<td>0.014 (0.004)</td>
<td>0.010 (0.004)</td>
</tr>
<tr>
<td>Norm NDF</td>
<td>0.014 (0.005)</td>
<td>0.010 (0.005)</td>
</tr>
</tbody>
</table>

*Normalized strength is a nondimensional quantity (Nm/Nm, see text).
**Dominant vs nondominant foot in absolute toe flexor strength, \(p = .228\).
†Gender effect for normalized toe flexor strength, \(p = .076\).
‡Age effect for normalized toe flexor strength, \(p = .002\).

Figure 2. The relationship between absolute toe flexor strength and the product of body weight times height for all subjects. The two regression lines, for the younger and older subjects, show that the young have greater toe flexor strength than the older subjects. It is noteworthy that the OM outlier with the greatest strength was an avid dancer.
rior to the MTJ, thereby maximizing the potential of R to arrest the body’s forward momentum (6). So, the functional toe length, which determines the maximum anterior limit of the FBOS relative to the MTJ, should correlate with the maximum toe flexor muscle strength, as was demonstrated over a range of subject body sizes (Figure 3).

The percentage functional toe length of the OA was found to be 28.3% less than that in the YA in this forward reach test. This result partly explains earlier findings in healthy subjects: King and colleagues (5) reported a 23% decrease in FBOS with age in a forward and backward lean test. It is noteworthy that the measured FBOS is approximately 11.9% larger in the reach test than in the lean test (6). That is why we used a forward reach, rather than lean, test to measure the anterior limit of the FBOS.

While the absolute toe flexor strength of men averaged 39% more than women, no gender difference was found after controlling for body size by normalization. These results are consistent with the 39% gender difference found in absolute ankle invertor and evertor muscle strengths during upright unipedal stance using a different test method, a result that was also found to scale with body size (13). Hence, both ankle and foot muscle strengths tend to scale with body size in healthy individuals. The age-related reduction in absolute toe flexor strength was 9% and 14% less in the women than the men. Although this finding could be associated with high-heeled shoe use (14) by some of the women, the lack of a corresponding gender difference in the normalized data does not support this explanation.

It might be argued that a limitation of the test is the fact that we did not measure individual moment contributions of each toe to S. While it is possible to make individual measurements using a similar test paradigm, it is the summed moment that dictates the anterior limit of the FBOS used for controlling sagittal plane sway, leans (5), or reaches. Our test method can be modified to accommodate patients who have difficulty balancing unipedally by providing a hand support, as long as its effect on the magnitude and direction of R is taken into account.

A patient with impaired toe flexor strength might be advised that he or she has a reduced FBOS upon which to conduct forward reach and other activities; when appropriate, a toe flexor strengthening program might be discussed.

We conclude that the smaller anterior FBOS in these healthy older subjects could only be due to the reduction in their toe flexor muscle strength, because none had foot deformities or a flexure contracture at an MTJ. The age-related reduction in toe flexor strength identified in this article helps explain the reduced FBOS available for the elderly in activities such as reaching (6), leaning and bending (5), balancing on a reduced base of support (15), or stopping quickly during locomotion (16).

Acknowledgments
This study was funded by the PHS Grants PO1 AG10542 and P60 AG 08808.

We thank Janet Kemp, Martin Stenzel, Cécile Smeesters, Heather Lilley, Jessica Ho, and Glenn McCabe for their assistance with this study.

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EFFECTS OF AGE ON TOE FLEXOR STRENGTH


Received August 2, 2001
Accepted December 3, 2001