Thresholds for Sensing Foot Dorsi- and Plantarflexion During Upright Stance: Effects of Age and Velocity

D. G. Thelen, C. Brockmiller, J. A. Ashton-Miller, A. B. Schultz, and N. B. Alexander

Background. The objective of this study was to determine in healthy young and old adult females the influence of age, rotation direction, angle, and speed on the threshold for sensing foot dorsi- and plantarflexion when standing and bearing weight on the limb.

Methods. Twelve young (YF, mean age 22 years) and 12 old (OF, 70 years) healthy adult females stood on their dominant foot on a servo-controlled platform and the other foot on a fixed platform. The platform induced either dorsi- or plantarflexion rotations at angular velocities of 0.1, 0.5, or 2.5°/s to angles of 0.05, 0.1, 0.2, 0.4, or 0.8°. Subjects performed five trials at each velocity-angle combination and 30 dummy trials in which no platform rotation occurred, for a total of 180 trials. Success rates were determined for detecting both rotation (SRR) and rotation direction (SRD) for each test condition. The angular thresholds required to achieve an SRD of 75% were estimated using logistic regression.

Results. Age, rotation angle, and rotation speed significantly affected SRD (repeated measures ANOVA; p < .001). For the YF: DF thresholds were 0.04, 0.09, and 0.41° at the fast, moderate, and slow velocities, respectively. Threshold angles were three to four times larger in the OF than in the YF. A 10-fold reduction in the angular threshold was observed upon increasing the speed of rotation from 0.1 to 2.5°/s.

Conclusions. Both age and speed significantly affected the thresholds for sensing foot dorsiflexion and plantarflexion in women.

Of the visual, vestibular, and proprioceptive sensory information that is used for the control of upright stance, proprioceptive afference from the lower extremities is usually relied upon most by the postural control system (1–3). It stands to reason, then, that impairments in lower-extremity proprioception can adversely affect the ability to remain upright, at least under more challenging conditions, and impaired ankle proprioception has indeed been shown to contribute to balance difficulties in the elderly (4–6). Therefore, a quantitative assessment of the effect of age on the ability to sense joint rotations may provide insights into the source of a subset of balance difficulties in the elderly.

Earlier methods for quantifying lower-extremity proprioception, usually made under non-weight-bearing conditions, have included determining the threshold for quantifying abilities to either match or replicate limb position (7–9) and quantifying the thresholds for the detection of joint rotation (10,11). An age effect has been demonstrated in that elderly have been shown to demonstrate larger errors than young when replicating joint angles (8). Moreover, the threshold for sensing passive rotations at the non-weight-bearing hip, knee, and ankle have been shown to be twice as large in subjects over 50 years of age as in subjects under 40 years of age (12), results since corroborated by others (8,10).

Recent studies have reported significantly lower proprioception thresholds in the weight-bearing lower extremity than in the non-weight-bearing extremity. In the sagittal plane, for example, Fitzpatrick and McCloskey (2) demonstrated that young adults were capable of detecting less than 0.2° angular perturbations of standing sway using ankle proprioception. In the frontal plane, Gilson et al. (13) demonstrated a threshold of .06° for detecting ankle inversion with a 75% rate of success while weight-bearing. Evidence that age also affects proprioceptive thresholds in the weight-bearing ankle comes from the frontal plane tests of Gilson et al., who demonstrated a significantly greater threshold value of 0.35° in healthy elderly compared to that found in healthy young adults. In contrast to the Fitzpatrick and McCloskey results, Simoneau et al. (14) found that a group of healthy middle-aged adults could detect sagittal plane rotations of 1.8° at 0.25°/s and 1.4° at 0.75°/s; the sevenfold difference in sagittal plane threshold between the two studies may partially be explained by the different subject group ages, but essentially the discrepancy remains unresolved. It remains to be shown that age significantly affects the sagittal-plane proprioceptive threshold in the weight-bearing ankle. Apart from studies of the effect of ankle rotation speeds ranging from 0.25 to 0.75°/s (14), up to 2.5°/s (2), and up to 12.5°/s (15), the effects of direction and speed on the ability to sense sagittal-plane rotations in the weight-bearing ankle have received limited attention; most such studies have been conducted in the non-weight-bearing ankle (e.g., 12,16).
The present study was therefore undertaken to quantify rates of success in the detection of foot dorsi- and plantarflexion when using the lower extremities to stand and bear weight, and to determine the effects of age, rotation magnitude, rotation direction, and rotation speed on ankle proprioception. We tested the hypotheses that, when standing and bearing weight, (a) age significantly affects the threshold for detecting foot dorsi- or plantarflexion rotations, and (b) the threshold for detecting these rotations is independent of direction and of rotation speed over the range 0.1–2.5°/s. The study was restricted to females because females outnumber males in the elderly population and because no significant gender differences in ankle proprioception have been found in younger or older individuals (13).

**METHODS**

Twelve healthy young [YF: mean (standard deviation, SD) age 21.8 (1.6) years, range 20–24 years] and 12 healthy old [OF: 69.7 (4.1) years, range 66–74 years] females participated. The mean (SD) heights of the YF and OF groups were 163.8 (4.8) cm and 156.9 (4.8) cm, respectively, while the mean weights were 66.2 (12.2) kg and 67.2 (13.4) kg, respectively. The YF were recruited from university staff and students, while the OF were recruited from independent community-dwelling elderly.

All OF initially denied significant musculoskeletal or neurologic impairment. During a standard clinical evaluation that focused on neurologic and musculoskeletal abnormalities, some subjects reported a distant history of musculoskeletal problems that did not interfere with daily function: rare, occasional pain in their lower extremities or lower back (N = 3); a previous fracture of an unspecified area of the foot, with no residual pain (N = 1); a previous ankle sprain with rare exertional-related pain (N = 1); and a previous lumbar vertebral fracture with no residual pain or neurologic sequelae (N = 2). Subjects did not report any symptoms related to these injuries during the study. In addition, four subjects had decreased but symmetric lower-extremity reflexes. All except two OF were physically active, with regular participation in walking, exercise, or sports activities.

Each subject stood bipedally with one foot, the foot she said she would use to kick a ball, placed on a servo-motor-driven platform (Figure 1). The subject’s foot was positioned such that a line through the medial and lateral malleoli was parallel with the axis of platform rotation, which lay 10 cm above the platform surface and approximately collinear with the center of rotation of the ankle joint in the sagittal plane. The subject’s other foot was placed on a fixed platform of equal height. The subject was asked to stand comfortably with approximately 50% of her weight on each foot and with her hands at her sides. We note that the 50% weight distribution on each foot was not measured but only voluntarily approximated by the subjects, because pilot experiments in five old and five young subjects showed that it can be maintained to within an accuracy of approximately 5% of body weight. Background music played through headphones worn by the subject masked any audible cues from the platform motor that could divide the subject’s attention.

The subject was asked to gaze at a light display placed 1.5 m straight in front of her. A black backdrop behind the light display was hung from the ceiling and gradually sloped forward to the floor to diminish visual reference cues. Light display illumination indicated the beginning of each trial. This was followed by a 0 to 1-s random delay prior to the platform beginning to rotate at a constant angular velocity to a specified angle. The light display remained illuminated for 9 s, the time required for the platform to rotate through the largest angle. When the display was turned off, the subject was asked to indicate verbally whether her foot had rotated up, down, or not at all, or had moved, but in an unknown direction. The platform was then returned slowly to its unrotated configuration prior to the next trial.

Subjects were tested using platform angular speeds of 0.1 (slow), 0.5 (medium), and 2.5°/s (fast) to angles of 0.05, 0.1, 0.2, 0.4, and 0.8° in both dorsiflexion (DF) and plantarflexion (PF). Body sway in response to such small and slow rotations of one foot was assumed negligible (see Dis-
Subjects performed five trials at each velocity-angle combination and 30 dummy trials in which no rotation occurred, for a total of 180 trials. The protocol was presented in five blocks of 36 initially randomized, fixed-order trials. Each of the blocks was performed as two sets of 18 trials with a 1-min rest between sets. Subjects were given a 3- to 5-min rest between blocks to lessen fatigue. The ordering of the trials in the first and fifth blocks was identical, so that the effects of cumulative practice and fatigue could be examined.

Subjects’ abilities to detect platform rotation were quantified by the number of trials in which either the occurrence of rotation and/or its direction was correctly detected. A rotation success rate (SR) was defined with regard to whether or not the occurrence of any rotation was correctly detected. A direction success rate (SDR) was correspondingly defined as the ratio of trials in which the direction of the rotation was correctly identified to the number of nonzero angle trials. SR and SDR were determined for each subject for each speed-angle combination and expressed in percent of the total number of trials conducted for that condition.

Repeated-measures analysis of variance (rm-ANOVA) was used to determine the effects of age, angle, direction, and speed on SRR and SDR. In tests of these primary hypotheses, p values less than .05 were considered statistically significant.

Cumulative success rates for each speed-angle combination were determined separately for YF and OF. At each velocity and separately for young and old, nonlinear logistic regression was used to relate success rate to angle. The identified regression equations were used to estimate the platform rotation angle required to achieve a nominal 75% success rate at a given velocity (13). That criterion was selected because we had earlier shown that statistical estimates of the detection threshold, commonly used in signal detection theory and psychophysical research (15,17), were consistent (13), and because estimates of the 100% threshold are too sensitive to small fluctuations in slope of the regression function in that region.

Cumulative practice and fatigue effects were examined by comparing SRD success rates in the first and fifth trial blocks. For each subject, the number of trials in which rotation direction was identified correctly in the first but incorrectly in the fifth (CI), and incorrectly in the first but correctly in the fifth (IC) blocks were determined. Cumulative learning and fatigue effects were assessed by using paired t tests to compare whether CI was different from IC.

**Results**

The results show that humans can consistently sense platform rotations of less than 1° in both dorsiflexion (DF) and plantarflexion (PF) during upright bipedal stance. Age (p < .0001), speed (p < .0001), and direction (p < .05) were found to have significant effects on the ability to detect both foot motion and direction (rm-ANOVA, Tables 1 and 2).

**Effect of Age on Proprioceptive Thresholds**

The hypothesis was supported in that YF consistently had greater rotation success rates (SRR) and direction success rates (SDR) than OF at every speed-angle combination tested. For example, SDR of the YF were greater than 78% for all of the 2.5°/s rotations, but they were as low as 30% for the OF at this speed.

The dummy, “no movement,” control trials were correctly identified by the YF with a 97% success rate, a 21%
Table 2. Effects of Direction, Angle, Age, and Speed on Mean Success Rates in Detecting the Direction of the Rotation

<table>
<thead>
<tr>
<th>Direction</th>
<th>Angle (deg)*</th>
<th>0.1%/</th>
<th>0.5%/</th>
<th>2.5%/</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YF‡</td>
<td>OF‡</td>
<td>YF‡</td>
<td>OF‡</td>
</tr>
<tr>
<td>PF§</td>
<td>0.05</td>
<td>0.28 (0.22)</td>
<td>0.08 (0.13)</td>
<td>0.38 (0.30)</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>0.35 (0.27)</td>
<td>0.20 (0.21)</td>
<td>0.47 (0.27)</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>0.52 (0.34)</td>
<td>0.37 (0.25)</td>
<td>0.77 (0.24)</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>0.58 (0.40)</td>
<td>0.33 (0.34)</td>
<td>0.88 (0.18)</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>0.83 (0.29)</td>
<td>0.52 (0.38)</td>
<td>0.97 (0.08)</td>
</tr>
<tr>
<td>DF§</td>
<td>0.05</td>
<td>0.30 (0.29)</td>
<td>0.23 (0.21)</td>
<td>0.48 (0.25)</td>
</tr>
<tr>
<td></td>
<td>0.10</td>
<td>0.25 (0.24)</td>
<td>0.20 (0.21)</td>
<td>0.63 (0.28)</td>
</tr>
<tr>
<td></td>
<td>0.20</td>
<td>0.45 (0.26)</td>
<td>0.33 (0.25)</td>
<td>0.87 (0.18)</td>
</tr>
<tr>
<td></td>
<td>0.40</td>
<td>0.58 (0.20)</td>
<td>0.47 (0.30)</td>
<td>0.95 (0.12)</td>
</tr>
<tr>
<td></td>
<td>0.80</td>
<td>0.75 (0.21)</td>
<td>0.67 (0.26)</td>
<td>0.98 (0.06)</td>
</tr>
</tbody>
</table>

Note: Standard deviations in parentheses.

*Angle, p < .0001.
‡Speed, p < .0001.
§Age, p < .001.
\$Direction, p < .03.
Angle × speed and angle × speed × age, p < .0001.
Angle × age, p < .05.

higher success rate than that of the OF. This is additional evidence that age affects the consistency with which foot rotations can be sensed.

The nonlinear regression models resulted in coefficients of determination (R²) better than .95. They showed that the YF thresholds for sensing the direction of platform rotation with a probability of 75% DF were 0.04, 0.09, and 0.41° at the fast, moderate, and slow velocities, respectively; DF threshold values for OF were 2.8 to 4 times larger. The corresponding YF values in planarflexion were 0.03, 0.16, and 0.43°, with OF having 3.2 to 4.3 times larger values than the YF (Table 3).

**Effect of Speed on Proprioceptive Threshold**

The hypothesis was rejected in that success rates generally improved with increasing angular speed for a given angle. For example, PF proprioceptive threshold angles for YF were 0.43° at the 0.1%/s speed, but less than 0.05° at the 2.5%/s speed. Similarly, while OF did not achieve a 75% SRD at the 0.1%/s speed for any of the angles presented, only 0.13° of PF rotation were required to achieve a 75% SRD at the 0.1%/s speed. For the YF a greater than 10-fold increase was observed in the angular threshold upon decreasing the speed of rotation from 2.5 to 0.1%/s (Table 3). For the OF a greater than three-fold increase in angular threshold was observed upon decreasing the speed from 2.5 to 0.5%/s; OF did not achieve a 75% SRD at the 0.1%/s speed for any of the angles presented.

**Effect of Rotation Direction**

The SRD were significantly different in dorsiflexion and plantarflexion (p < .05, ANOVA) with rotation directions generally being detected with slightly greater reliability in DF than in PF.

Table 3. Average Angular Thresholds (°) for Correctly Detecting the Direction of Ankle Rotation With a Nominal 75% Success Rate, as Estimated by Nonlinear Regression Models of the Form SRD = exp(B0 + B1*Angle)/(1 + exp(B0 + B1*Angle))

<table>
<thead>
<tr>
<th>Speed</th>
<th>Dorsiflexion</th>
<th>Plantarflexion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YF</td>
<td>OF</td>
</tr>
<tr>
<td>0.1%/s</td>
<td>0.51</td>
<td>*</td>
</tr>
<tr>
<td>0.5%/s</td>
<td>0.09</td>
<td>0.36</td>
</tr>
<tr>
<td>2.5%/s</td>
<td>0.04</td>
<td>0.11</td>
</tr>
</tbody>
</table>

*OF did not achieve a 75% success rate for any of the angles presented at the 0.1%/s velocity.

**Interactions**

Significant interaction effects were found in the angle × age and angle × speed × age interactions (Tables 1 and 2). These interactions appeared to result from the inclusion of (large) speeds and/or angles for which both YF and OF achieved nearly 100% success rates. For example at the 2.5%/s speed, YF and OF exceeded 97% success rates for the 0.4 and 0.8° angles. Thus, while there were substantial differences between the success rates of Y and O at low speed and small angles, those differences were not present as angle and speed increased and each group achieved near 100% accuracy.

**Comparison of SRD and SRR**

SRD values ranged up to 60% lower than the corresponding SRR values while following similar trends with respect to speed and angle effects.

**Cumulative Practice and Fatigue Effects**

No pronounced changes in performance over the duration of the test were found. Comparisons of results from the
Table 4. Cumulative Practice and Fatigue Effects
From the First to Fifth Blocks of Trials*

<table>
<thead>
<tr>
<th></th>
<th>CC</th>
<th>CI</th>
<th>IC</th>
<th>II</th>
</tr>
</thead>
<tbody>
<tr>
<td>YF</td>
<td>17.5(3.5)</td>
<td>5.1(3.3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OF</td>
<td>10.7(3.3)</td>
<td>4.9(3.0)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The mean (SD) number of trials is given in which the subject was correct in the first and fifth blocks (CC), correct in the first and incorrect in the fifth (CI), incorrect in the first and correct in the fifth (IC), and incorrect in both blocks (II).

CI not significantly different from IC via paired t tests (p = .057).

first and fifth trial blocks for CI (number of trials in which direction was identified correctly in the first and incorrectly in the fifth trial block) and IC (number of trials in which direction was identified incorrectly in the first and correctly in the fifth trial block) showed that the improvement in SRS with practice did not attain significance in either YF or OF (Table 4), suggesting that practice and fatigue effects might have balanced one another. On average, YF responded consistently (either both correct or both incorrect) in the first and fifth trial blocks for 75% of the nonzero-angle trials, while OF responded consistently for 73% of the nonzero-angle trials.

DISCUSSION
The results demonstrate that the consistency with which a healthy adult can detect small sagittal-plane rotations of the foot in upright stance is substantially diminished by age. This result is consistent with known age effects in ankle inversion/eversion (13), knee (8), and hip (12) proprioception. We doubt that the age effect was attributable to the subtle musculoskeletal abnormalities found in the elderly (Methods), because the mean SRS of the six subjects with past injuries, over all trials, was 51%, which actually exceeded the mean 47% overall SRS achieved by the older individuals as a group.

In this study we have quantified the smallest magnitude of foot rotation that subjects can perceive at a conscious level. As we have argued earlier with regard to inversion/eversion thresholds (13), we cannot exclude the possibility that while smaller rotations might not be perceived at the conscious level, they could still be detected subconsciously at the subcortical level. While such sensed, yet unperceived, rotations may be smaller than those reported here, they cannot be larger, so the present estimates are likely conservative. Comparison of the success rates in Tables 1 and 2 shows that the threshold for the detection of motion (SRR) is smaller than the threshold for specifying the direction of rotation (SRD) and is consistent with previous studies (12,18).

The detection of platform rotation can involve visual, vestibular, proprioceptive, and cutaneous pressure sensation feedback. Fitzpatrick and McCloskey (3) found muscle afferents to provide more reliable proprioceptive information than vestibular or visual receptors. Vision likely played an insigificant role in the present tests, both because the black backdrop did not provide fixed visual reference points and because the presence or absence of visual feed-

back did not affect success rates in our earlier study (13). With rotations of less than 1° applied to only one ankle during bipedal stance, it is unlikely that these small and slow rotations induced sway responses sufficient to stimulate the vestibular organs (2). Support for this view comes from similar threshold magnitudes being found whether (13) or not constraints were used to eliminate possible sway-related tibial rotations. By not using such constraints in this experiment, we eliminated the possibility of a subject using cues from reaction forces at the tibial constraint. Thus we surmise that afference from lower-extremity muscle spindles and plantar pressor receptors is the likely proprioceptive source used by these subjects.

These healthy young and old adults were able to perceive platform rotations less than 1° during upright stance. This finding is consistent with the angular thresholds found for ankle rotations in the frontal plane in the weight-bearing extremity (13) as well as the magnitude of angular sway disturbances detectable using only ankle proprioception (2,3). The present SRR and SRS thresholds are up to an order of magnitude smaller than those of the nonweight-bearing ankle (9,19). A possible explanation for this improved proprioception includes the successful use of pressure change cues from weight-bearing plantar pressor receptors (13). In addition, the extended knee posture associated with standing is also thought to augment input from the elongated calf muscle intramuscular receptors when compared with the flexed-knee seated posture (17).

An important finding is that the threshold for detecting rotation at the ankle increased by a factor of 10 from the highest angular speed (2.5°/s) to the slowest angular speed (0.1°/s). This rate sensitivity was evident in young and old adults, and is consistent with earlier findings (10,14,15-17); it is also characteristic of most sensory receptors, because receptor adaptation facilitates the perception of the rate of change of a stimulus as well as the absolute sensation itself. The slowest testing speed we used is representative of ankle angle rotational velocities commonly observed during postural sway (20). Phase differences between the directions of platform and body sway could have contributed to threshold variability at the slowest speed, but the random nature of the effect would be independent of test direction, and thus our estimate of the slow-speed detection threshold is probably conservative. Whereas the present study found the threshold to be speed-sensitive, our earlier study did not (13). The results are, however, complementary — the present study involved rotations from 0.5 to 2.5°/s, whereas the earlier study involved speeds greater than 2.0°/s. The evidence from these and other (15) studies suggests that the speed effect appears to saturate above 5°/s. In summary, the important insight is that the older women sensed slow changes in standing posture less consistently than rapid changes. We argue that the significant interactions we found do not detract from the major conclusions because they were likely caused by the successful detection of large amplitude and speed rotations by both groups.

Lower-limb sensory deficits are known to affect the ability to maintain balance under challenging circumstances. First, the experimental restriction of foot sole pressure sensation and/or ankle proprioception are known to increase
postural sway during upright stance (2,21,22). Second, and more important from a gerontologic perspective, documented mild to moderate peripheral neuropathy, known to impair foot and ankle proprioception (14,23), is associated with substantially worse unipedal balance performance than in age-matched elderly controls (24), especially in poor lighting (6), and is thought to contribute to the sixfold increase in injurious falls in this patient population (25). So, the possibility of age-related proprioceptive deficits should be considered whenever elderly report, or are reported to have, difficulties with balance whenever visual feedback is diminished, as at dusk or in the dark (6).

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