Variability and Symmetry of Force Platform Variables in Maximum-Speed Running in Young and Older Athletes

Marko T. Korhonen, Harri Suominen, Jukka T. Viitasalo, Tuomas Liikavainio, Markku Alen, and Antti A. Mero

Eighteen young (23 ± 4 yr) and 25 older (70 ± 4 yr) male sprinters were examined for ground reaction force (GRF) and temporal-spatial variables. The data were collected during maximum-speed phase, and variability and symmetry indices were calculated from a total of 8 steps. There was little variation (CV < 6%) in vertical and resultant GRF and kinematic variables, while impact loading had high variability (CV: 10–21%). Overall, the pattern of variability was similar in both groups. Yet, a small but significant age-related increase in CV was evident in horizontal GRFs. There was a variable-specific asymmetry between legs but it was not related to leg dominance. No age differences existed in the symmetry indices. Results indicate that only selected force platform variables are symmetric and repeatable enough so that their use for comparison purposes is appropriate. Data also suggest that aging may increase variability in certain biomechanical measures, whereas symmetry is not affected by age.

Keywords: biomechanics, ground reaction forces, repeatability, reliability, locomotion, aging

With aging the ability to run fast declines progressively (Hamilton, 1993; Korhonen et al., 2003, 2009; Roberts et al., 1997). Although the previous studies have described nature of the age-related decline in maximum running speed, no authors have addressed the effect of aging on the parameter variability and symmetry. The knowledge of the degree of variability has importance for experimental work in indicating which measures can confidently detect small training- or age-related changes in an athlete’s performance. Examination of symmetry has also direct relevance for the data collection indicating whether unilateral trials give symmetrical values for different variables, and provides insight into the potential functional imbalance of neuromuscular performance.

Investigations on young runners have indicated that many basic temporal-spatial and ground reaction force (GRF) variables of sprinting show relatively small intra-individual variability, and that a large number of trials/steps may not be required to obtain stable and reliable data (Bradshaw et al., 2007; Hunter et al., 2004; Mero & Komi, 1986). However, these investigations have provided no conclusive evidence, because the only study (Mero & Komi, 1986) that investigated the variability during maximum-speed running was limited to two GRF variables and the other studies (Bradshaw et al., 2007; Hunter et al., 2004) focused accelerated sprinting excluding direct comparison with the maximum-speed running. Furthermore, with increasing age reproducing the complex movement pattern of sprinting may become more challenging as the neuromuscular system and motor control deteriorates (Spirduso, 2001).

In most sprint running studies, the biomechanical variables have been measured on only one side of the body, with the assumption that similar results would be obtained for the contralateral side. However, studies regarding symmetry during submaximal-speed running (at 2.9–6.8 m·s⁻¹) in young athletes have indicated that symmetry in biomechanical measures between opposing legs cannot be automatically presumed (Belli et al., 1995; Williams et al., 1987). Moreover, there is some evidence to suggest that leg dominance/preference can increase asymmetry during submaximal-speed running and walking, because the dominant leg may be more responsible for propulsion, whereas the nondominant leg plays a stabilizing function (Sadeghi et al., 2000). However, it remains unclear whether these findings on slow running or walking apply to sprint running with much higher force and movement speed requirements. Moreover, aging could increase asymmetry in sprinting due to an increase in bilateral asymmetry in muscle power and force production of lower limbs (Perry et al., 2007).
Despite the importance of parameter repeatability and symmetry for accurate performance assessment, there is a lack of information of these components in sprint running. Therefore, the purpose of this investigation was to determine variability and symmetry of force platform measures of maximum-speed sprinting in young and older runners. We took as our first hypothesis that older age is associated with increased parameter variability in sprint running. Our second hypothesis was that older age leads to increased performance asymmetry during maximal running.

Methods

Eighteen young adult (age 23 ± 4 yrs) and 25 older (age 70 ± 4 yrs) sprinters were examined during preseason. The young participants were taller (1.79 ± 0.04 m vs. 1.72 ± 0.04 m, p < .001) and heavier (77 ± 6 kg vs. 71 ± 8 kg, p = .007) than the participants in the older group. However, this may not significantly influence our results as the forces were normalized to body weight, and the age-related difference in step length was similar when adjusted or unadjusted for the differences in body height. The weekly training hours were 10.8 ± 2.1 for young and 8 kg, respectively. Thirteen of the young participants and 18 of the older participants were right-footed. A strength test (David Rehab 2200 dynamometer, David Fitness and Medical, Helsinki, Finland) of a subset of participants indicated that isometric knee extension torque was, on average, 3.7% and 5.0% higher in the dominant leg than in the nondominant leg for the young (n = 15) and older (n = 18) participants, respectively. Thirteen of the young participants and 18 of the older participants were midfoot strikers, and the rest were forefoot strikers. (The forefoot strikers did not show an initial vertical impact force, F\textsubscript{z,impact}, Figure 1a.) According to the medical histories and focused medical examination, all participants were healthy and free of musculoskeletal or neurological impairments which may affect the normal sprint running pattern. This study was approved by the Ethics Committee of the University of Jyväskylä, and written informed consent was obtained from the participants.

After a warm-up of about 30–45 min and several submaximal practice trials, the participants performed two maximal 30-m sprints and two maximal 60-m sprints. The sprints were performed from a standing start in spiked running shoes on an indoor synthetic track that was bordered by an open area of 6–10 m on both sides. A rest interval between each run of 5–7 min was given so as to avoid neuromuscular fatigue, which may lead to loss of maximal performance and an increase in the variability of the sprinting movement pattern.

Vertical and horizontal GRFs and step temporal-spatial variables were measured during the maximum-speed phase of the 60-m trials (from 30 m onwards) using a 9.4-m long force platform system. The force platform system consisted of nine tartan-surfaced force plates (five 2-D and three three-dimensional force plates, 0.9 × 1.0 m, natural frequency ≥ 170 Hz, nonlinearity ≤ 1%, cross talk ≤ 2%, TR-test, Jyväskylä, Finland; and one Kistler three-dimensional force plate, 0.9 × 0.9 m, natural frequency 400 Hz, Kistler, Winterthur, Switzerland) connected in series. The force platform system was firmly attached to a concrete base that was set below the track surface. The force signals were sampled at 1000 Hz and stored on a microcomputer via an AT Codas A/D converter card (Dataqa Instruments, Akron, OH, USA). The sprints over the force platform were also videotaped (Redlake Motionspace, 500 C; 125 Hz; 1/500; Redlake, San Diego, CA, USA) in lateral view to evaluate the foot-strike pattern during a run. The camera field of view was 9 m, and showed all the foot contacts on the force platform system that were used in the biomechanical analyses. Step length, L\textsubscript{step}, was measured (to 0.5 cm) from spike marks on a thin paper sheet that was firmly attached over the force platform (the paper was changed after about every fourth trial). In our previous measurements on young sprinters the difference between this paper method and film analysis was ±2 cm (A. Mero, unpublished observation). However, due to the potential errors related to the video analyses (digitization process), the measurement of L\textsubscript{step} is likely to be more accurate by using the paper method (exact spike marks) and was therefore used in this study. The maximal 10-m sprint velocity and 60-m sprint times were obtained using double-beam photocell gates. In addition, a laser radar (Laveg Sport; Jenoptik, Jena, Germany) positioned 6 m behind the start line, was used to analyze the instantaneous running speeds of the athletes. The results showed that the athletes achieved 99–100% of their maximum speed in the 30- to 40-m distance used for force platform measurements.

The force platform data were analyzed using custom-written software. Vertical and horizontal antero-posterior force-time curves and the resultant force vector diagram are shown in Figure 1. The variables describing the maximum rate of impact loading and the average rate of impact loading were calculated from the initial part of the vertical force-time trace (Gottschall & Kram, 2005). The maximum rate of impact loading, LR\textsubscript{max}, was defined as the greatest instantaneous slope of the GRF trace (Figure 1a):

$$LR_{\text{max}} = \max \left\{ \frac{dF_z(t)}{dt} \right\}$$

(1)
The average rate of impact loading, $LR_{ave}$, was defined as

$$LR_{ave} = \frac{F_{z_{\text{impact}}}}{\Delta t}$$

(2)

where $\Delta t$ is the time interval from the beginning of the ground contact to the instant of the impact peak, $F_{z_{\text{impact}}}$.

Note that while $LR_{max}$ was determined for all the athletes, $LR_{ave}$ could be calculated for those 13 of 18 young and 18 of 25 older runners who did exhibit $F_{z_{\text{impact}}}$. However, because the performance of these athletes did not differ from those without $F_{z_{\text{impact}}}$, we wanted to include also $LR_{ave}$ and $F_{z_{\text{impact}}}$ parameters in this study to provide additional information about age-related differences in impact loading in sprint running.

The other GRF variables included the maximal and average values of the vertical ($F_z$), horizontal antero-posterior ($F_y$), and resultant ($F_r$) forces. The resultant GRF was a 2-D vector composed of the vertical anterior/posterior GRF components. The transition point from negative to positive values in the anterior-posterior GRF curve was used to divide the force components into braking and propulsion phases (Mero & Komi, 1986). For these analyses, a vertical force threshold of 20N was used to identify the beginning and end of the ground contact. Of the temporal variables, contact time ($t_{\text{contact}}$), aerial time ($t_{\text{aerial}}$), and step frequency ($Freq_{\text{step}} = 1/(t_{\text{contact}} + t_{\text{aerial}})$) were obtained from the force-time traces. The dominant side step for the parameters of $t_{\text{aerial}}$, $Freq_{\text{step}}$, and $L_{\text{step}}$.

The figure shows an example of (a) vertical and (b) horizontal force-time curves, and (c) the resultant force vector diagram of the first right foot contact for a young sprinter with midfoot strike while running at 10.0 m·s⁻¹. In panel c, the diagram illustrates the changes in magnitude and orientation of the resultant GRF through the contact. A vertical broken line in the first contact (a-c) indicates the border between the braking and push-off phases. $F_{z_{\text{max}}}$ = maximal vertical force, $F_{z_{\text{impact}}}$ = vertical impact force, $LR_{max}$ = maximum rate of impact loading (the greatest instantaneous slope in the vertical GRF), $LR_{ave}$ = average rate of impact loading ($F_{z_{\text{impact}}}$ / the time interval from the beginning of the ground contact to the instant of the impact peak), $F_{y_{\text{brake-max}}}$ = maximal horizontal braking force, $F_{y_{\text{push-max}}}$ = maximal horizontal push-off force, $F_{r_{\text{brake-max}}}$ = maximal resultant braking force, $F_{r_{\text{push-max}}}$ = maximal resultant push-off force, $t_{\text{contact}}$ = ground contact time, $t_{\text{aerial}}$ = aerial time, bw = body weight.
was defined as the step that begins from the dominant leg contact (dominant side \( F_{\text{step}} \) included the \( t_{\text{contact}} \) of the dominant leg).

The asymmetry between dominant and nondominant leg variables was quantified with a symmetry index (SI; Herzog et al., 1989);

\[
SI(\%) = \left( \frac{X_D - X_{ND}}{1/2( X_D + X_{ND})} \right) \times 100\% \tag{3}
\]

where \( X_D \) is the variable for the dominant leg, and \( X_{ND} \) is the variable for the nondominant leg. When SI of the individual is zero, there is perfect symmetry between the legs. A positive SI indicates a higher value for the dominant leg than for the nondominant leg, and a negative SI indicates a lower value for the dominant leg than for the nondominant leg. The data were also examined using the absolute symmetry index, \( ASI = |SI| \), so that averaging positive and negative symmetry indices over several participants does not lead to a zero value (Giakas & Baltzopoulos, 1997).

Each trial involved 4–6 contacts on the force platform. For consistency, the first four contacts of the two trials were taken in the analyses for each participant. In the analyses the values for the dominant leg and nondominant leg were calculated from the two trials and averaged intraindividually. Furthermore, the forces were normalized to body weight (bw) to allow comparisons between participants.

All statistical analyses were performed using SPSS 16.0 software (SPSS Inc., Chicago, IL, USA). The coefficient of variation, \( CV = (SD/\text{mean}) \times 100 \), was calculated to assess the relative intraindividual variability of the variables for the dominant leg and for the nondominant leg. In the force platform measurements, the errors related to instrumentation and scoring are small and the major source of variability is expected to be due to the biovariation associated with human movement (Hamill & McNiven, 1990). A 2 × 2 MANOVA (two age groups × two sides) was used to examine the influence of age and leg dominance on the CV values (Figure 2). Age group comparisons for the mean values of all the dependent variables (dominant and nondominant side values pooled together), and symmetry indices (SI and ASI) were made using ANOVA (Table 1). A paired \( t \) test, with Holm correction for multiple comparisons, was used to compare the mean values of the GRF and step temporal-spatial variables between dominant and nondominant legs within groups. Test-retest comparison of maximum running speed and 60-m running time within groups was made using paired \( t \) tests. Simple (bivariate) linear regression analyses were performed in pooled data to determine the association of ASI, SI and magnitudes of the kinematic and GRF measures (mean of dominant and nondominant side) with maximum running speed. Of the GRFs, only the main components (maximal and average vertical and horizontal forces) were selected in the regression analysis. The level of significance was set to \( p < .05 \).

Results

Older age was associated with a decline in maximum running speed (9.50 ± 0.42 m s\(^{-1}\) vs. 7.30 ± 0.57 m s\(^{-1}\), \( p < .001 \)) and an increase in the 60-m times (7.09 ± 0.21 s vs. 9.06 ± 0.65 s, \( p < .001 \)). For vertical GRFs, the young participants produced a greater \( LR_{\text{ave}} \) (\( p = .009 \)), \( F_{x_{\text{ave}}} \) (\( p < .001 \)) and \( F_{z_{\text{ave}}} \) (\( p < .001 \)), whereas \( LR_{\text{max}} \) was similar (\( p = .177 \)), and \( F_{\text{impact}} \) lower (\( p = .012 \)) in the young participants than in the older participants. All the horizontal GRFs showed higher values for the young participants than for the older participants (all \( p < .001 \)). The resultant GRFs, \( F_{\text{brake-max}} \) (\( p = .022 \)), \( F_{\text{brake-ave}} \) (\( p < .001 \)), \( F_{\text{push-max}} \) (\( p < .001 \)), and \( F_{\text{push-ave}} \) (\( p < .001 \)) were higher in the young participants than in the older participants.

For the temporal-spatial variables, the young participants had a shorter \( t_{\text{contact}} \) and a greater \( t_{\text{final}} \), \( F_{\text{step}} \) and \( L_{\text{ave}} \) compared with the older participants (all \( p < .01 \)). When \( L_{\text{ave}} \) and \( F_{\text{step}} \) were calculated in relation to body height, the age-related decline remained significant for \( L_{\text{ave}} / \text{body height ratio} = 1.20 \pm 0.03 \) vs. 1.03 \pm 0.06 m/m; \( p < .01 \) but not for \( F_{\text{step}} / \text{body height} = 2.47 \pm 0.15 \) vs. 2.41 \pm 0.18 Hz/m; \( p = .274 \).

The CVs ranged from 1.5% to 17.4% in the young participants, and from 1.4% to 21.1% in the older participants (Figure 2). In general, the variation in both groups was low (CV < 6%) in the vertical and resultant forces and in all the step temporal-spatial variables, but clearly higher for vertical loading (\( LR_{\text{ave}} \), \( LR_{\text{ave}} \), \( F_{z_{\text{max}}} \)) and horizontal forces. The test-retest CV values for the maximum speed and 60-m times were 0.6 ± 0.3% and 0.4 ± 0.2% in the young group of participants, and 0.7 ± 0.5% and 0.5 ± 0.5% in the older group of participants, respectively.

The CVs of \( LR_{\text{max}} \) (\( p = .037 \)), \( F_{y_{\text{brake-max}}} \) (\( p < .001 \)), \( F_{y_{\text{push-max}}} \) (\( p < .001 \)), \( F_{y_{\text{push-ave}}} \) (\( p = .003 \), and \( t_{\text{final}} \) (\( p < .001 \)) showed higher variability in the older participants than in the younger participants (Figure 2). In these parameters, the CV values (mean of dominant and nondominant side) were an average 37% higher in the older than young group, while the absolute magnitude of the difference was an average 3.0 CV% (3.4 CV% for \( LR_{\text{max}} \), 3.4 CV% for horizontal GRFs and 1.5 CV% for \( t_{\text{final}} \)). The magnitude of age-related difference in CVs was quite similar for dominant and nondominant side in all measures, excluding \( LR_{\text{max}} \) in which the nondominant side CV values were only slightly higher (5% or 0.5 CV%) in the older than in young group. No effect of lateral dominance on the CV values was observed.

There were no differences in the variable mean values between the dominant and nondominant legs in either group (Table 1). The symmetry index (SI) ranged from −5.4% to +5.6% in the young group, and from −2.6% to +2.7% in older group (Table 1). There was one significant age-related difference in the symmetry index, with older participants showing greater asymmetry for \( t_{\text{aryl}} \) than older participants (\( p = .037 \)).

The absolute interleg asymmetry (ASI) values ranged from 2.7% to 14.3% in the young group, and from 2.2%
Table 1: The components of the GRFs and temporal-spatial stride parameters of sprint running for the dominant and nondominant sides, and the symmetry indices (SI, ASI) in young and older subjects

<table>
<thead>
<tr>
<th></th>
<th>Young Runners 9.50 ± 0.42 m/s</th>
<th></th>
<th></th>
<th></th>
<th>Older Runners 7.30 ± 0.57 m/s</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dominant</td>
<td>Nondominant</td>
<td>SI %</td>
<td>ASI %</td>
<td>Dominant</td>
<td>Nondominant</td>
<td>SI %</td>
<td>ASI %</td>
</tr>
<tr>
<td><strong>Vertical force</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(L_{R_{max}} \text{ (bw/s)})</td>
<td>418 ± 58</td>
<td>418 ± 56</td>
<td>-0.6 ± 15.4</td>
<td>11.8 ± 9.9</td>
<td>338 ± 121</td>
<td>339 ± 112</td>
<td>0.6 ± 20.4</td>
<td>18.1 ± 11.3</td>
</tr>
<tr>
<td>(L_{R_{ave}} \text{ (bw/s)})</td>
<td>211 ± 32</td>
<td>206 ± 26</td>
<td>1.7 ± 15.9</td>
<td>11.2 ± 11.0</td>
<td>193 ± 59</td>
<td>195 ± 60</td>
<td>-1.3 ± 25.6</td>
<td>18.8 ± 16.8</td>
</tr>
<tr>
<td>(F_{z_{impact}} \text{ (bw)})</td>
<td>2.01 ± 0.79</td>
<td>2.12 ± 0.72</td>
<td>-5.4 ± 15.4</td>
<td>13.5 ± 8.5</td>
<td>3.20 ± 0.64</td>
<td>3.29 ± 0.69</td>
<td>-2.6 ± 16.7</td>
<td>10.1 ± 13.4</td>
</tr>
<tr>
<td>(F_{z_{max}} \text{ (bw)})</td>
<td>3.34 ± 0.25</td>
<td>3.35 ± 0.26</td>
<td>-0.3 ± 6.8</td>
<td>3.8 ± 2.6</td>
<td>2.82 ± 0.34</td>
<td>2.83 ± 0.33</td>
<td>-0.3 ± 4.0</td>
<td>2.2 ± 1.6*</td>
</tr>
<tr>
<td>(F_{z_{ave}} \text{ (bw)})</td>
<td>2.07 ± 0.13</td>
<td>2.02 ± 0.10</td>
<td>2.0 ± 4.5</td>
<td>3.8 ± 3.1</td>
<td>1.85 ± 0.19</td>
<td>1.85 ± 0.20</td>
<td>0.5 ± 4.8</td>
<td>4.1 ± 2.7</td>
</tr>
<tr>
<td><strong>Horizontal force</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{y_{brake_max}} \text{ (bw)})</td>
<td>1.42 ± 0.17</td>
<td>1.43 ± 0.24</td>
<td>0.6 ± 15.8</td>
<td>13.7 ± 7.8</td>
<td>0.88 ± 0.20</td>
<td>0.91 ± 0.26</td>
<td>-2.0 ± 22.6</td>
<td>18.3 ± 14.3</td>
</tr>
<tr>
<td>(F_{y_{brake_ave}} \text{ (bw)})</td>
<td>0.40 ± 0.04</td>
<td>0.41 ± 0.06</td>
<td>-0.3 ± 17.0</td>
<td>14.3 ± 9.8</td>
<td>0.31 ± 0.04</td>
<td>0.32 ± 0.05</td>
<td>-1.9 ± 22.1</td>
<td>17.4 ± 15.2</td>
</tr>
<tr>
<td>(F_{y_{push_max}} \text{ (bw)})</td>
<td>0.74 ± 0.09</td>
<td>0.73 ± 0.08</td>
<td>3.0 ± 7.9</td>
<td>6.5 ± 5.2</td>
<td>0.50 ± 0.07</td>
<td>0.50 ± 0.07</td>
<td>2.7 ± 6.8</td>
<td>6.5 ± 3.7</td>
</tr>
<tr>
<td>(F_{y_{push_ave}} \text{ (bw)})</td>
<td>0.41 ± 0.03</td>
<td>0.40 ± 0.04</td>
<td>2.9 ± 11.3</td>
<td>10.1 ± 5.7</td>
<td>0.29 ± 0.04</td>
<td>0.28 ± 0.03</td>
<td>2.1 ± 11.1</td>
<td>9.7 ± 6.5</td>
</tr>
<tr>
<td><strong>Resultant force</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(F_{r_{brake_max}} \text{ (bw)})</td>
<td>3.76 ± 0.63</td>
<td>3.52 ± 0.38</td>
<td>5.6 ± 11.0</td>
<td>9.6 ± 7.7</td>
<td>3.29 ± 0.50</td>
<td>3.26 ± 0.57</td>
<td>1.5 ± 8.6</td>
<td>6.1 ± 6.5</td>
</tr>
<tr>
<td>(F_{r_{brake_ave}} \text{ (bw)})</td>
<td>2.70 ± 0.25</td>
<td>2.62 ± 0.17</td>
<td>2.8 ± 6.7</td>
<td>5.8 ± 4.4</td>
<td>2.40 ± 0.29</td>
<td>2.39 ± 0.30</td>
<td>0.7 ± 4.7</td>
<td>4.1 ± 2.7</td>
</tr>
<tr>
<td>(F_{r_{push_max}} \text{ (bw)})</td>
<td>3.08 ± 0.21</td>
<td>3.05 ± 0.25</td>
<td>0.5 ± 6.5</td>
<td>4.2 ± 4.4</td>
<td>2.74 ± 0.31</td>
<td>2.74 ± 0.31</td>
<td>-0.2 ± 5.6</td>
<td>4.8 ± 3.0</td>
</tr>
<tr>
<td>(F_{r_{push_ave}} \text{ (bw)})</td>
<td>1.90 ± 0.15</td>
<td>1.87 ± 0.17</td>
<td>0.4 ± 6.6</td>
<td>3.9 ± 4.3</td>
<td>1.61 ± 0.19</td>
<td>1.62 ± 0.18</td>
<td>-0.3 ± 6.8</td>
<td>5.9 ± 3.5</td>
</tr>
<tr>
<td><strong>Temporal-spatial parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(t_{contact} \text{ (ms)})</td>
<td>102 ± 7</td>
<td>101 ± 7</td>
<td>1.4 ± 4.7</td>
<td>4.0 ± 2.9</td>
<td>129 ± 16</td>
<td>127 ± 16</td>
<td>1.5 ± 3.6</td>
<td>3.3 ± 2.1</td>
</tr>
<tr>
<td>(t_{aerial} \text{ (ms)})</td>
<td>129 ± 11</td>
<td>123 ± 9</td>
<td>5.0 ± 8.1</td>
<td>8.0 ± 5.2</td>
<td>116 ± 9</td>
<td>117 ± 12</td>
<td>-0.6 ± 8.7*</td>
<td>7.3 ± 5.0</td>
</tr>
<tr>
<td>(Freq_{step} \text{ (Hz)})</td>
<td>4.34 ± 0.25</td>
<td>4.49 ± 0.25</td>
<td>-3.6 ± 5.8</td>
<td>5.7 ± 3.8</td>
<td>4.14 ± 0.27</td>
<td>4.16 ± 0.30</td>
<td>-0.4 ± 5.0</td>
<td>4.0 ± 3.1</td>
</tr>
<tr>
<td>(L_{step} \text{ (m)})</td>
<td>2.16 ± 0.07</td>
<td>2.13 ± 0.07</td>
<td>1.7 ± 3.2</td>
<td>2.7 ± 2.3</td>
<td>1.77 ± 0.10</td>
<td>1.77 ± 0.12</td>
<td>-0.2 ± 3.0</td>
<td>2.6 ± 1.6</td>
</tr>
</tbody>
</table>

Note. Values are group means ± SD. Number of subjects = 18 young and 25 older subjects (a these variables could be determined only for the midfoot strikers, \(n = 13\) young and 18 older runners). *Significantly different (\(P < .05\)) from the corresponding value in the young group (indicated by bold numbers). bw = body weight. See text and Figure 1 for description of the parameters.
to 18.8% in the older group (Table 1). Age had a significant effect on absolute symmetry index of $F_{z_{\text{max}}}$ that was higher in the young (3.8%) than in older (2.2%) group ($p = .016$).

The simple (bivariate) linear regressions in pooled data did not result in significant associations of $ASI$ or $SI$ with maximum running speed. In contrast, the magnitudes of the kinematic and GRF measures showed relationship with maximum speed. The strongest kinematic predictors of maximum running speed were $L_{\text{step}}$ ($R^2 = .70$, or $R^2 = .80$ when adjusted to body height, $p < .001$ in both) and $t_{\text{contact}}$ ($R^2 = .70, p < .001$) followed by $Freq_{\text{step}}$ ($R^2 = .48, p < .001$, or $R^2 = .16$ when adjusted to body height, $p < .01$) and $t_{\text{aerial}}$ ($R^2 = .18, p < .01$). Of the GRF parameters, the most significant predictors of maximum running speed were $F_{y_{\text{brake-max}}}$ and $F_{y_{\text{push-max}}}$ (both $R^2 = .79, p < .001$). Next in the prediction accuracy were $F_{y_{\text{brake-ave}}}$ ($R^2 = .59$), $F_{y_{\text{brake-ave}}}$ ($R^2 = .54$), $F_{z_{\text{max}}}$ ($R^2 = .53$) and $F_{z_{\text{ave}}}$ ($R^2 = .31$; all $p < .001$).

**Discussion**

The primary new findings from the present investigations were as follows. First, among the many commonly used force platform variables only step temporal-spatial ($L_{\text{step}}, Freq_{\text{step}}, t_{\text{contact}}$) and selected vertical ($F_{z_{\text{max}}}, F_{z_{\text{ave}}}$) and resultant ($F_{y_{\text{brake-ave}}}, F_{y_{\text{push-max}}, F_{y_{\text{push-ave}}}}$) GRF variables provided repeatable and symmetric values during maximum-speed running. Second, although the pattern of variability was found to be quite similar for the young and older runners, some small, but statistically significant age-related increases in CV values were found, particularly in the horizontal GRFs. This finding provides partial support for the hypothesis that aging leads to increased variability in sprinting. Third, the data also suggest that symmetry of the biomechanical measures is not affected by age, thus not supporting our second hypothesis of age-related increase in asymmetry.

The present investigation demonstrated that in both age groups the CVs of all the temporal-spatial variables and selected vertical and resultant GRF variables were less than 6% (Figure 2). These variables can be suitable for interindividual comparisons and reliable enough to identify the relatively small training-induced changes in an athlete’s performance. For example, in a recent study (Cristea et al., 2008) older sprinters showed 3% and 8% increases in $L_{\text{step}}$ and $F_{y_{\text{push-ave}}}$ in response to training that are likely to be detected by the variability levels of 1.5% and 5.5%, respectively, observed in this investigation. In contrast, all the vertical loading and some horizontal GRF ($F_{y_{\text{brake-max}}, F_{y_{\text{brake-ave}}}}$) variables demonstrated larger variability (CV > 10%) in the present work and should be used with caution for sprint assessment. On the other
hand, the higher CV% of $LR_{\text{max}}$ compared with other parameters is not unexpected since it is the derivative of vertical GRF as a function of time. In addition, the relatively large CV% values of horizontal GRFs reflect, in part, the low absolute values of these variables.

Our results about the magnitude of variability in the force platform measures are in line with the findings of the only available study on the variability of maximum-speed sprinting (Mero & Komi, 1986). The study examined reproducibility of $F_{\text{brake-ave}}$ and $F_{\text{push-ave}}$ during maximal speed phase (35–45 m; 8.8–10.2 m/s) in 11 male and 8 female young adult competitive sprinters (Mero & Komi, 1986). The CV for the $F_{\text{brake}}$ of two right foot contact was 7.3% and 5.1% during the braking and push-off phase, respectively. However, the study was limited to two GRF measures. Accordingly, the current study is the first to provide more comprehensive information on the variability and symmetry of the measures during maximum-speed sprinting and provide for basis of comparison for future studies.

Older runners exhibited greater CV than young runners for the variables describing the horizontal braking and push-off GRFs, maximal vertical loading rate, and aerial time (Figure 2). On the other hand, the difference seems to be consistent only in the horizontal GRF component where 3 of 4 examined parameters showed age-related increase in the CV values. With age there was an average 39% increase in variability in horizontal GRFs; however, the absolute magnitude of difference was only about 3–4 CV%. Therefore, it is arguable whether these small, albeit statistically significant differences in CV values have any practical significance in the accuracy of biomechanical assessment. On the basis of the data by Hunter et al. (2004) such small differences in CVs can be meaningful and help estimating how many trials/steps need to be collected. For example, the CV% of braking GRF impulse was 14.2% for one step but improved to 8.2% and 6.3% when using average score of 3 and 5 steps, respectively. It is thus possible that while more trials are necessary for horizontal GRFs in both age groups, one or two additional steps are required for the older runners to reach the same accuracy of the measurement than in young athletes. It should be emphasized here that in single testing session it is not possible to collect many overall (60 m, 100 m) sprint trials without increase of the fatigue-related variability in the measurements. Therefore, using shorter distances, e.g., flying start 10–20 m sprint trials, could permit a few extra trials without fatigue effect and improve CV of horizontal GRFs to a level that training- and aging-related changes can be reliably detected. Further study examining parameter variability of increasing number of sprint trials is warranted to extend the present findings and to verify if small statistical significance can reach practical significance.

The mechanism of the increased in variability was not addressed in this study and could only be cautiously speculated based on data of nonsprint activities. Overall control of locomotor movements requires integration of central nervous system with sensory inputs (visual, vestibular, proprioceptive) to produce appropriate motor response (Dietz, 2003). Evidence also suggests that complex networks of neurons located in the spinal cord (central pattern generators), with the control of higher centers and feedback from peripheral receptors, are important for the automated rhythmic movement generation in locomotion (Dietz, 2003; Dimitrijevic et al., 1998; Grillner, 1981). Age-related degeneration within the central or peripheral nervous system may lead to impairment in automatic pattern generation and increase variability in locomotion (Prince et al., 1997). For example, recent study including a large sample of healthy older adults ($n = 558$, 79.4 ± 4.1 yrs) showed that increased variability in contact time in walking was related to impairment in the central nervous system, whereas step width variability was related to sensory impairment (Brach et al., 2008). Studies have also provided evidence that the nervous system’s ability to control leg muscle force generation is impaired with age, particularly in eccentric contractions (Carville et al., 2007; Christou & Carlton, 2002). Thus, one possibility is that aging sprint athletes experience impairment in the force control by nervous system, which is reflected in an increased in variability in the biomechanical parameters. However, if the neuromuscular force control was the mechanism, one might expect significant CV differences also in vertical GRFs that are on average 5 times greater than horizontal GRFs; this did not occur suggesting that other mechanism may be responsible.

Some authors assume that increased variability in horizontal braking and push-off GRFs could be due to differences in running style. In their study Lees and Bouracrer (1994) examined loading and horizontal GRFs in 7 experienced and 7 inexperienced male runners during over-ground 60-m running trials (4.7–5.2 m/s). The inexperienced runners showed greater variability in braking and push-off impulses (running style variables), whereas there were no group differences in variability in $LR_{\text{max}}$, $LR_{\text{ave}}$, or $F_{\text{impact}}$. Further, nonrunners had similar $LR_{\text{max}}$ and $LR_{\text{ave}}$, but higher $F_{\text{impact}}$ that can reflect a heavier heel strike and reduced shock absorption ability. Those group differences in GRF pattern seem to be quite similar to those found between young and older sprinters in the current study. Accordingly, it is possible that in the older runners, who spent significantly smaller amount of time in weekly practice, the foot strike pattern with higher $F_{\text{impact}}$ has played role in the increase in variability. Another potential explanation for increased parameter variability could be greater fluctuations in the step-by-step velocity. This issue should be examined in further studies.

Preferred use and superior performance and skill of one leg versus the other is commonly observed for various motor activities (Peters, 1988). This may be due to genetically determined brain laterality that is intensified by increased use of one side in daily activities and exercise (Gabbard & Hart, 1996; Peters, 1988). The SI values between the dominant and nondominant legs of this study seem to suggest no effect of lateral dominance on sprint running (Table 1). Our result is in line with some studies of slow running (Hamill et al., 1984) and walking (Gundersen et al., 1989; Hamill et al., 1984).
The SI equation is “limited” in that pooled data across participants can lead to a zero value, if some participants show superior measurements by the dominant leg and some superior by nondominant leg. When we did not take into account leg dominance but examined only interleg differences, the ASI symmetry values ranged from 2.7% to 14.3% (mean 7.8%) in young and from 2.2% to 18.8% (mean 7.8%) in older runners. According to this result, marked variable-specific asymmetries between legs are present during sprinting, supporting previous studies on submaximal-speed running (Belli et al., 1995; Vagenas & Hoshizaki, 1992; Williams et al., 1987; Zifchock et al., 2006). The smallest ASI values (≤ 6%) were found in selected temporal-spatial variables (Lstep, Freqstep, Fcontact) and vertical (Fz_max, Fz_avg) and resultant GRFs (Frake_avg, Frpush_avg) and might be expected to reflect, in part, small variability of these parameters.

The SI and ASI results provided evidence that older age has no effect on symmetry during sprint running at maximal force effort. These results do support earlier findings of interleg asymmetry during walking in healthy individuals of different age (Liikavainio et al., 2007; Menz et al., 2004; Stacoff et al., 2005). One could thus infer that increased asymmetry in different modes of human locomotion is not a normal concomitant of aging.

The maintenance of symmetry in older runners may indicate that although the structure and function of neuromuscular locomotor system show age-related degeneration, the movement coordination and force characteristics of each side of the body are similarly affected by age. It is partially supported by our finding on isometric strength test showing that in older athletes the strength advantage of the dominant leg was 5%, which compared quite well to that (3.7%) in young runners. In sprint running the stride pattern is highly dependent on the ability to tolerate the great contact forces. Thus, if strength asymmetry is large, it could affect symmetry in maximal running.

Neural basis of bilateral symmetry in human running is not known and is very difficult to investigate. However, studies have provided insight into the neural mechanisms responsible for left-right coordination in walking that may apply to running. Some investigators have assumed that the primary site of symmetry regulation during walking is the central pattern generator of the spinal cord (Yogev et al., 2007). Studies using split-belt treadmill have suggested that there are autonomous pattern generators for each leg that communicates with its counterpart for the contralateral leg to ensure bilateral coordination (Dietz et al., 1994; Yang et al., 2005). The regulation of symmetry may also rely on proprioceptive feedback (Dietz et al., 1994), and control by higher centers that is evidenced by excessive asymmetry in people with certain unilateral central nervous system pathology (Wall & Turnbull, 1986). Accordingly, the lack of any significant difference between the asymmetry of biomechanical parameters in young and older runners in this study suggests that the capacity of integrated neuromuscular system to coordinate very fast symmetric movements is not compromised by aging. This may partially reflect favorable effects of lifelong training on movement coordination (Spirduso, 2001). To clarify this point it would be interesting to compare older athletes and nonathletes in locomotion, motor control, and structure and function of the brain.

Taken together, our results suggest that asymmetry in biomechanical variables of sprint running is not influenced by age, vary with the parameter of interest, and cannot be predicted from leg dominance. Unilateral leg examination may not be representative and this should be taken into account for comprehensive sprint performance evaluation. Furthermore, the observation that asymmetry was not related to leg dominance raises a question as to whether general definitions used for leg dominance (e.g., leg used for one-foot jumping or kicking a ball) are valid for locomotion action (Sadeghi et al., 2000). In this regard, determination of absolute interleg differences (ASI) could be a more appropriate method for estimating symmetry in sprint running.

While the current results suggest small age effect on symmetry and variability of force platform parameters, substantial differences were observed in the magnitude of the kinematic and GRF measures between the young and older athletes. As to kinematic nature of the decline in maximum running speed with age, it was related primarily to the changes in Lstep and Fcontact, whereas smaller change was found in Freqstep. The regression analysis indicated that Lstep and Fcontact can account for 80% and 70% of the variance in running speed, respectively. The results of GRFs showed greater age-related decline in horizontal braking (–22 to –38%) and push-off (–29 to –32%) than in vertical (–8 to –16%) GRFs. Furthermore, it was found that horizontal push-off GRFs explained larger portion of the variance in maximum speed ($R^2 = .79$) than horizontal braking ($R^2 = .54–.59$) or vertical ($R^2 = .31–.53$) GRFs. These new findings suggest differences in the GRF pattern so that young runners reach higher maximum running speeds by a technique that intensify horizontal propulsive forces. However, such a technique requires very high torque-producing capabilities of the hamstrings and hip extensors and may not be applicable or efficient for the weaker older runners.

Certain limitations of our study should be pointed out. First, in the current study the measurements were taken on the same day. Information regarding interday repeatability is needed to complement the findings of the current study. Second, our study sample consisted only of highly-trained competitive male sprinters. The reproducibility and symmetry of biomechanical variables may be different in female athletes or inexperienced runners. Third, a limitation of the study is the relatively small number of steps analyzed. However, we believe that a larger number of maximal overall sprint trials are not practically possible for runners to perform without a confounding fatigue effect, and that it is important to establish the reliability of assessment tasks that are applicable to normal training and competition situations.

On the other hand, a main advantage of the current study was that the measurements were made using a unique long force platform system which allowed the
recording of consecutive steps bilaterally during the same trial. This significantly cut time in data collection and is likely to reduce the targeting-, velocity-, and fatigue-induced variability in the measurement which may be a matter for concern when a single force plate with multiple maximal sprint trials is used (Abendroth-Smith, 1996; Hunter et al., 2004). Actually, based on previous study by Hunter et al. (2004), with single force plate method about 7–8 sprints are needed to obtain 4–5 successful ground contacts for one side.

In conclusion, these results indicate that only selected force platform variables are symmetric and repeatable enough so that their use for experimental work and comparison purposes is appropriate. Our data also provide evidence that older age may lead to small but significant increase variability, especially in horizontal GRF variables of sprint running, whereas the symmetry of the biomechanical measures may not be affected by age. In contrast to endurance running and walking, studies evaluating the reliability of biomechanical variables in sprint running have been very limited. This lack of knowledge must be regarded as a serious problem that may influence the accuracy of performance assessment and could lead to wrong conclusions. Thus the present data have potentially important implications and can be used as a reference in the selection of biomechanical variables designed to investigate sprint performance in young and older runners.

Acknowledgments
This study was supported by the grants from the Finnish Ministry of Education, the Peurunka Medical Rehabilitation Foundation, Ellen and Artturi Nyyssönen Foundation, and National Graduate School for Musculoskeletal Disorders and Biomaterials. The authors thank Timo Annala, Milan Sedliak, Minna Märd and Tuovi Nykänen for valuable assistance with the data collection and analysis, and all the athletes participating in this study.

References


