Functional Asymmetries and Lateral Dominance in the Lower Limbs of Distance Runners

George Vagenas and Blaine Hoshizaki

This study investigated the phenomenon of lower extremity functional asymmetries in a group of competitive male distance runners (N=29). Bilateral measurements were taken to assess selected variables of the talocalcaneal flexibility (goniometry) and of the isokinetic knee strength (Cybex II). Data analysis revealed significant asymmetries for both lower extremity functional parameters. The subjects were symmetric in the total range of motion of the subtalar joint and inversely asymmetric in the range of motion of calcaneal eversion and calcaneal inversion. The laterality patterns of functional asymmetries were found to be consistent and independent of the conventional upper and lower extremity lateral preferences. It was theorized that asymmetries in the lower extremities are characterized by joint-specific trends of bilateralism.

Anatomical variabilities and asymmetries are developed during growth and determined by genetic and environmental factors (Pande & Singh, 1971; Prives, 1960; Zaichkowsky, Zaichkowsky, & Martinek, 1980). The influence of heredity predetermines the preferred side of the body for several basic motor functions, while environmental sources exert facilitating or inhibitory "pressures" upon the state of sidedness in each motor function (Chhibber & Singh, 1970; Cratty, 1970). As a result of this interaction, the human body develops asymmetries in anthropometric dimensions (Cavanagh & Preece, 1981; Chhibber & Singh, 1970; Dogra & Singh, 1971; Latimer & Lowrance, 1965; LeMay, 1977; Mascie-Taylor, McLarnon, Lanigan, & McManus, 1981; Subotnick, 1976), muscle strength (Damholt & Termansen, 1978; Gillies & Chalmers, 1970; Thorngren & Werner, 1979), and flexibility (Agre et al., 1987; Hoehler & Tobis, 1982; Warren, 1984).

One of the most significant parameters in the assessment of the normality of lower extremity function in runners is the flexibility of the subtalar joint (Brody, 1980). In a research paper on the biomechanical profiling of elite dis-
Nomenclature

PTCF  Passive talocalcaneal flexibility
EVEROM  Eversion range of motion
INVROM  Inversion range of motion
TOTROM  Total range of motion
EVEINV  Eversion to Inversion range-of-motion ratio
PIKS  Peak isokinetic knee strength
FLESTR  Flexion strength
EXTSTR  Extension strength
TOTSTR  Total strength
FLEEXT  Flexion to Extension ratio
Ia  Indices of percent asymmetry
Li  Laterality indices
Ma  Mean asymmetries
f  Frequencies
C  Contingency coefficients
%c  Percent concordances
WH  Writing hand
DH  Drawing hand
TH  Throwing hand
KL  Kicking leg
HJL  High jumping leg
LJL  Long jumping leg
L  Left side
R  Right side

tance runners, Cavanagh et al. (1985) reported asymmetries in the range of motion in calcaneal eversion and inversion, and in the calcaneal angle from a standing position. Similar results were found by Warren (1984) in a study on the prediction of plantar fasciitis in long-distance runners on the basis of selected anatomical factors. Warren measured pronation as the angle between the midline of the leg and the midline of the calcaneus, with the subject in the weight-bearing standing position, and reported mean pronation values that presented striking differences between the left and right foot.

Clinical investigators have stated that functional abnormalities and variations are related to the etiology of running injuries (Clancy, 1980; Drez, 1980; Subotnick, 1976). Clarke, Frederick, and Hamill (1984) emphasized the importance of flexibility in the subtalar joint, which allows the foot to be a “mobile adapter” immediately following touchdown in order to compensate for anatomical abnormalities in its structure. Therefore a potential asymmetry in foot pronation may predispose the feet of the runner to asymmetrical shock-absorbing mechanisms.

Another critical parameter that is frequently used in the biomechanical evaluation of lower extremity function in runners relates to muscle strength imbalances. Experimental studies have demonstrated that the lower extremities of athletes are not symmetric in muscular strength recordings produced during bicycle ergometer pedaling (Daly & Cavanagh, 1976), isometric knee extension
Similar trends of asymmetries have also been found in experiments testing the capacity of the knee flexor and extensor muscles to produce peak isokinetic force (Gilliam, Sady, Freedson, & Villanacci, 1979; Goslin & Carteris, 1979; Pipes & Wilmore, 1975). Based on clinical assessments, strength imbalances in the quadriceps and hamstring muscles have been implicated in increasing the risk of knee injury (Klein, 1983; Knight, 1980) and of muscle and joint injury in general (Coplin, 1971). The clinical significance of disturbances in hamstring and quadriceps function to the etiology of overuse injuries may be increased in runners with excessive pronation (Taunton, Clement, Smart, & McNicol, 1987).

A thorough search in the pertinent literature revealed no studies focusing on the problem of functional asymmetry in athletes and particularly in runners. Given the clinical and biomechanical importance of asymmetries, the present experimental study was designed to statistically determine whether the lower limbs of distance runners are asymmetric in selected critical variables characterizing the range of motion of the subtalar joint and the strength of the quadriceps and hamstrings muscles.

**Methods and Procedures**

**Subjects**

A total of 29 male long-distance runners volunteered to participate in the study. All were healthy and free of injuries or symptoms at the time of the experiment; their mean age was 23.3 (±2.7) years, mean body mass was 68.6 (±5.5) Kg, and mean height was 176 (±6) cm. Their training patterns ranged from 2 to 12 years of running, from 6 to 12 months of consistent training per year, from 20 to 160 Km of training distance per week, from 3.67 to 4.92 min/Km of year average training pace, and from 5 to 52 Km of favored running event.

Selected trichotomous nominal data (L, R, and L=R) reflecting the state of conventional lateral dominance (preference) of each runner was collected. The preferred side of the body was identified for the writing hand (WH), the drawing hand (DH), the throwing hand (TH), the kicking leg (KL), the high jumping leg (HJL), and the long jumping leg (LJL). The criteria employed to collect these data were based on highly reliable items chosen from standardized questionnaires (Annett, 1985; Raczkowski & Kalat, 1974) and clinical research (Singh, 1970). Subjects' reliability (n=14) in identifying the body side for each qualitative descriptor of lateral preference was very high. The coefficients of reliability were significant and took the values \( \alpha = 0.83 \) (LJL), \( \alpha = 0.84 \) (HJL), and \( \alpha = 1.00 \) (WH, DH, TH, KL).

**Talocalcaneal Flexibility Testing and Analysis**

The degree of passive flexibility of the subtalar joint was measured with a mechanical goniometer (Brody, 1980). The conventional methods of assessing leg/heel alignment (American Academy of Orthopaedic Surgeons, 1965; Brody, 1980) and range of subtalar joint motion (James, Bates, & Osternig, 1978) were employed (Figure 1). This manual goniometric technique was chosen in order...
PASSIVE TALO-CALCANEAL FLEXIBILITY (PTCF):

1. EVerSion ROM (EVEROM)
2. INVersion ROM (INVROM)
3. TOTal ROM (TOTROM) = EVEROM + INVROM
4. EVERom/INVrom ratio (EVEINV)

Figure 1 — Anatomical model of passive inversion and eversion of the talocalcaneal joint (right leg, rear view).

to produce data useful for clinical diagnosis and kinesiological assessment of functional lower limb problems (American Academy, 1965).

The subject assumed a prone position on a bench with both feet hanging equally over the bench edge. The midlines of the posterior aspect of the lower shank and the rearfoot (calcaneal region) were drawn on both legs of each runner. The center of the goniometer was placed on top of the calcaneal tuberosity with its central line coinciding with the reference line of the leg segment. The ruler was lined up with the reference midline of the rearfoot. The foot was then maximally inverted (supinated) by passive rotation of both the calcaneus and the forefoot simultaneously (Brody, 1980), and the free end of the ruler was adjusted to the new position of the calcaneus.

The angle indicated on the goniometer by the other end of the ruler was recorded with an accuracy of ±1°. The calcaneus and the forefoot were then rotated to the opposite direction to reach the maximum everted position (pronated), goniometric lines were checked again, and the new reading was recorded. The procedure was applied twice and then repeated on the opposite foot. Special attention was given to avoid movement of the skin around the markers.

The maximum inverted and everted positions of the calcaneus were assumed to be at the physical limits of anatomical interlocking between the talus and the calcaneus. Reliability measurements were conducted (n = 14) at a second session using identical testing methods. The reliability coefficients were significant (p<0.01) and took the values of α = 0.95 (L) and α = 0.94 (R) for eversion range of motion (EVEROM), and α = 0.98 (L) and α = 0.99 (R) for inversion range of motion (INVROM).
The variables that were measured directly on each leg included the EVEROM and the INVROM. The description of passive talocalcaneal flexibility (PTCF) was completed by the inclusion of total range of motion (TOTROM), as the sum of EVEROM and INVROM, and the EVEROM to INVROM ratio (EVEINV), as an expression of EVEROM normalized to INVROM. The average individual scores of the four dependent variables for each foot were rearranged to express PTCF dominance specific to the functional criterion of calcaneal eversion (EVEROM). For each subject, the foot with the greater degree of EVEROM was classified as dominant.

The choice of EVEROM as an overall criterion of PTCF dominance was based on the assumption that passive eversion may constitute a structural constraint for maximum pronation during weight acceptance in running. In addition, static calcaneal eversion is an indicator of the normality of foot function (Brody, 1980; Cavanagh et al., 1985), while leg/heel alignment and the range of motion of the subtalar joint are considered as important factors of the lower extremity anatomy of the runner. Their assessment can provide valuable information about the normal or abnormal function of the foot during running (James et al., 1978).

Isokinetic Knee Strength Testing and Analysis

Peak torques applied by isokinetic contraction of the knee flexor and extensor muscles of each leg were measured on a Cybex II device. The test-retest reliability of the device ($r=0.99$) and its validity ($r=0.94$) for the measurement of maximum knee torque at a preset constant rate have been determined elsewhere (Lesmes, Costill, Coyle, & Fink, 1978; Moffroid, Whipple, Hofkosh, Lowman, & Thistle, 1969; Pipes & Wilmore, 1975). Peak knee flexion/extension muscle strength has become a key measurement in comparing injured and uninjured legs in athletes (Elliott, 1978). The speed of 60°/s was chosen as optimal for the isokinetic testing of maximum strength (isolated-joint testing and the Cybex II testing charts).

After a general body warm-up, the subject was seated with the trunk supported in the erect position and thighs firmly stabilized by the straps on the chair of the Cybex. The lower leg was fastened to the distal part of the lever arm directly above the anterior aspect of the tibiotalar joint, and the anatomical axis of the knee joint was aligned with the axis of rotation of the dynamometer shaft. Three submaximal-effort knee flexion/extension trials were performed to allow the subject to become familiar with the exercise and establish a satisfactory level of warm-up specific to the dynamic requirements of alternating hamstring to quadriceps contractions.

Two sets of four maximal effort trials were then performed over the first 90° range of motion of the knee joint, starting with the leg in full extension. A minimum of 3 minutes of rest was given between sets of the same side to decrease the effect of fatigue. After a 5-min resting period, the procedure was performed on the opposite side. Emphasis was placed on administering identical testing procedures for the left and right sides.

Peak torque values were obtained from the recordings of the torque-angular displacement curves in millimeters and then converted to ft lb (3.6 ft lb/mm) and to Nm (1 ft lb = 1.356 Nm). The variables that were measured directly from the graphic outputs (Figure 2) were flexion strength (FLESTR) and extension strength (EXTSTR). The description of the peak isokinetic knee strength (PIKS)
was completed by the inclusion of total strength (TOTSTR) as the sum of FLESTR and EXTSTR, and of flexion to extension ratio (FLEEXT) as an expression of FLESTR normalized to EXTSTR. One score for each of the four PIKS variables was computed from each tested trial.

The individual subject average scores in each variable and for each side were calculated from the eight scores obtained in each tested knee. Total strength (TOTSTR) was chosen as the best criterion to express lateral dominance specific to the general state of peak isokinetic knee strength capacity (PIKS dominance). For each subject, the leg with the higher average score in TOTSTR was categorized as stronger and therefore dominant to the contralateral leg. The average individual scores of the left and right sides in each of the four variables were then rearranged to express PIKS dominance.

Subject consistency in reproducing PIKS values for both the FLESTR and EXTSTR variables was subjectively assessed from the Cybex II graphic outputs (Figure 2). In addition, a test-retest reliability analysis (n=29) indicated that subjects were consistent in their PIKS outputs within and between sides for the two sets of trials. The reliability coefficients were significant (p<0.01) and took the values of α=0.94 (L) and α=0.96 (R) for knee flexion strength (FLESTR), and α=0.94 (L) and α=0.95 (R) for knee extension strength (EXTSTR).

**Statistical Procedures**

The sample’s mean quantitative characteristics were analyzed by descriptive statistics, while frequency analysis and descriptive statistics were used to evaluate the conventional (preferred) lateral dominance characteristics and the pattern of
Functional Asymmetries and Lateral Dominance

Functional asymmetries. Multivariate and univariate statistical comparisons were performed between the dominant (D) and nondominant (ND) sides of the body and between the left (L) and right (R) sides in order to establish the significance of the selected asymmetries. Wilks’ lambda multivariate criterion test statistic (Rao’s F approximation to lambda) was chosen to test the significance of each multivariate comparison (Pedhazur, 1982).

Reliability analyses were carried out and Cronbach’s alpha reliability coefficients for repeated measurements were computed for the lateral dominance, PTCF, and PIKS measures. Nonparametric relationships between the different asymmetry variables were estimated by phi (ϕ) correlation coefficients for dichotomous data (L, R), and by contingency (C) coefficients for trichotomous data (L, R, L=R). Phi coefficients were corrected (ϕr) to be interpretable as Pearson’s r (Morehouse & Stull, 1975), while the number (c) and percent (%c) concordances between the directions of the functional asymmetries were also computed. All statistical analyses were tested for significance at the 0.05 probability level.

Analysis and Results

Lower Extremity Functional Asymmetries

To test the extent and significance of overall functional asymmetry, three selected sets of PTCF and PIKS variables were subjected to multivariate analysis (Table 1). The first set included the variables EVEROM, INVROM, and EVEINV, and represented the PTCF component. The second set included the variables FLESTR, EXTSTR, and FLEEXT, and represented the PIKS component. The third set included the above six variables and represented both functional compo-

<table>
<thead>
<tr>
<th>Variable</th>
<th>Set no.</th>
<th>Dominant M</th>
<th>SD</th>
<th>Nondominant M</th>
<th>SD</th>
<th>F</th>
<th>Ma</th>
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<td>10.21</td>
<td>3.94</td>
<td>6.17</td>
<td>3.97</td>
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<tr>
<td>INVROM (deg)</td>
<td>1,3</td>
<td>20.21</td>
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<td>23.59</td>
<td>6.16</td>
<td>12.35*</td>
<td>-3.38</td>
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<td>9.37</td>
<td>29.76</td>
<td>8.09</td>
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<td>0.65</td>
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<tr>
<td>EVEINV (-)</td>
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<td>0.52</td>
<td>0.18</td>
<td>0.27</td>
<td>0.16</td>
<td>67.90**</td>
<td>0.25</td>
</tr>
<tr>
<td>FLESTR (Nm)</td>
<td>2,3</td>
<td>106.34</td>
<td>22.62</td>
<td>98.48</td>
<td>24.23</td>
<td>16.52**</td>
<td>7.86</td>
</tr>
<tr>
<td>EXTSTR (Nm)</td>
<td>2,3</td>
<td>185.48</td>
<td>35.86</td>
<td>169.72</td>
<td>32.23</td>
<td>99.42**</td>
<td>15.76</td>
</tr>
<tr>
<td>TOTSTR (Nm)</td>
<td>@</td>
<td>291.82</td>
<td>56.35</td>
<td>268.20</td>
<td>53.54</td>
<td>81.00**</td>
<td>23.62</td>
</tr>
<tr>
<td>FLEEXT (-)</td>
<td>2,3</td>
<td>0.57</td>
<td>0.06</td>
<td>0.58</td>
<td>0.09</td>
<td>67.90**</td>
<td>-0.01</td>
</tr>
</tbody>
</table>

*p<0.01; **p<0.001.

@Composite variables, not included in the multivariate analysis.
nents (PTCF, PIKS) of the lower limbs. The variables TOTROM and TOTSTR were excluded from these sets of multivariate comparisons, as being composites of EVEROM and INVROM, and of FLESTR and EXTSTR, respectively; they were simply subjected to univariate comparisons.

The results of the multivariate analysis, along with the results of the follow-up univariate comparison statistics of the six nonredundant and the two composite variables (TOTROM and TOTSTR), are given in Table 1. The differences between the mean vectors of the dominant (D) and nondominant (ND) sides (mean asymmetries [Ma]) were highly significant in all multivariate comparisons. More specifically, the statistical indices for the three sets of comparisons were, Wilks’ lambda $= 0.23532, F(3,26) = 28.16, p<.001$ for Set 1; $0.19832, F(3,26) = 35.03, p<.001$ for Set 2; and $0.13213, F(6,23) = 25.18, p<.001$ for Set 3. This demonstrated the existence of significant multifaceted functional asymmetry in the lower limbs of long-distance runners. The follow-up analyses indicated that all univariate asymmetries were significant except for the variable TOTROM.

A further analytical step was then undertaken to compare the mean values of the left (L) and right (R) sides (Table 2), in order to provide data for comparison with previous estimates of directional asymmetry. The three multivariate comparisons were found to be significant ($p<0.05$), indicating the existence of an overall trend for the left and right sides to present functional differences. The statistical indices for the three sets of comparisons were, Wilks’ lambda $= 0.71602, F(3,26) = 3.44, p<.05$ for Set 1; $0.73919, F(3,26) = 3.06, p<.05$ for Set 2; and $0.60100, F(6,23) = 2.54, p<.05$ for Set 3. However, the follow-up univariate comparisons revealed that the differences were statistically significant only for variables EVEROM and EVEINV, favoring the left side.

The mean univariate asymmetries (Ma) of the PTCF and the PIKS functional components were converted to indices of percent asymmetry (la) (Figure 3). In addition, frequencies (f) and laterality indices (Li) were computed for the

<table>
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<th>Table 2</th>
<th>Descriptive and Univariate Statistics and Mean Values for the Directional Functional Asymmetries of the Lower Limbs</th>
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<tbody>
<tr>
<td>Variable</td>
<td>Set no.</td>
</tr>
<tr>
<td>EVEROM (deg)</td>
<td>1,3</td>
</tr>
<tr>
<td>INVROM (deg)</td>
<td>1,3</td>
</tr>
<tr>
<td>TOTROM (deg)</td>
<td>@</td>
</tr>
<tr>
<td>EVEINV (-)</td>
<td>1,3</td>
</tr>
<tr>
<td>FLESTR (Nm)</td>
<td>2,3</td>
</tr>
<tr>
<td>EXTSTR (Nm)</td>
<td>2,3</td>
</tr>
<tr>
<td>TOTSTR (Nm)</td>
<td>@</td>
</tr>
<tr>
<td>FLEEXT (-)</td>
<td>2,3</td>
</tr>
</tbody>
</table>

*p<0.05; **p<0.01.

@Composite variables, not included in the multivariate analysis.
fluctuating asymmetries in order to obtain a quantitative estimate of the laterality patterns of each asymmetry variable. Li values were calculated for each of the three possible categories of laterality: superiority of the left side (L>R), superiority of the right side (R>L), and the category of symmetry (L=R). Quantitative symmetry was established in accordance with the condition |Ma| ≤ 1%, which classified all bilateral differences less than or equal to 1% as symmetries.

The greatest mean asymmetry for the PTCF variables (upper half of Table 1) was that of EVEROM (Ma = 4.04°), which accounted for Ia = 39.6% (Figure 3) of the mean EVEROM score achieved by the dominant (D) foot. The greatest index of asymmetry was that of EVEINV (Ia = 48.1%), which indicated that when maximum eversion is expressed as percentage of maximum inversion, the bilateral differences become even greater. The lesser mean asymmetry was shown by variable TOTROM, this being less than 1° (Ia = 2.1%) and statistically not significant. Yet the most noticeable trend of this part of Table 1 was the bipolarity between the variables EVEROM and INVROM.

This trend was also shown by the results of the laterality analysis (Figure 4). In 19 cases (Li = 65.5%) the left foot was found to be more flexible in eversion whereas the right foot was more flexible in the range of inversion in 17 cases (Li = 58.6%). For the variable TOTROM, the left side was dominant in 16 subjects (Li = 55.2%) and the right side was dominant in 10 subjects (Li = 34.5%), while in the remaining 3 cases (Li = 10.3%) symmetry was found. The most distinct laterality pattern was shown by EVEINV. The left foot in 20 subjects (Li = 69.0%) and the right foot in 9 subjects (Li = 31.0%) presented a lesser degree of imbalance between maximum pronation (EVEROM) and maximum supination (INVROM) compared to the contralateral foot.
All four PIKS asymmetry variables were statistically significant (lower half of Table 1). The largest mean asymmetry value was that of TOTSTR ($M_a = 23.62$ Nm), which accounted for $I_a = 8.1\%$ (Figure 3) of the mean TOTSTR score achieved by the dominant (D) foot. The greatest index of asymmetry was that of EXTSTR ($I_a = 8.5\%$), while the lesser mean asymmetry was shown by variable FLEEXT, this asymmetry being less than 2% even though statistically significant.

On the other hand, it appears that lateralization for FLESTR, EXTSTR, and TOTSTR strength did not favor either side of the body (Figure 5), since the left and the right leg was dominant in about an equal number of cases. However, when FLESTR was expressed as percentage of EXTSTR (FLEEXT), a distinct pattern of lateralization is shown in favor of the left leg ($f = 18$ and $L_i = 62.1\%$ for the R>L category). Therefore, despite the relatively small asymmetry in FLEEXT (1.75\%), this parameter appears to constitute a highly sensitive index for detecting even subtle strength imbalances between the flexor and extensor muscles of the knee joint in athletes.

**Interrelationships of Lateral Dominance Traits**

Figure 6 reveals a clear-cut superiority of the right side in upper limb lateral preference and in the kicking leg (KL). The average laterality index ($L_i$) values for these descriptors were 12.6 for left-sided dominance (L) and 87.3 for right-sided dominance (R). In addition, a moderate superiority of the left side in the high jumping leg (HJL) and in the long jumping leg (LJL) was observed, this being indicated by average $L_i$ values of 59.55 and 40.45 for the L and R categories, respectively.
Figure 5 — Patterns of laterality for the peak isokinetic knee (flexion/extension) strength (PIKS) variables.

Figure 6 — Patterns of lateral preferences for the conventional upper and lower limb dominance.
Some patterns of relationship were identified when the PTCF and PIKS variables were subjected to correlation analysis (Table 3). The objective was to obtain an assessment of the degree of association between these two components of the runner's lower extremity function. It was observed that in 21 subjects (c = 72%) the two criterion dominances (EVEROM and TOTSTR) favored the same side of the body: left side in 13 cases (44.8%) and right side in 8 cases (27.6%). Overall, there was a 58.6% trend to left-side dominance compared to a 41.4% trend to right-side dominance. EVEROM and TOTSTR were significantly correlated (φ = 0.46, φr = 0.66). This suggested interdependence between these two joint-specific lateral dominances. An even higher qualitative correlation was found between EVEINV and TOTSTR (φ = 0.54, φr = 0.75). In 22 subjects the lateralizations favored the same side of the body (%c = 76). All qualitative correlations for EXTSTR and TOTSTR with the rest of the variables were identical due to perfect concordance between these two variables in terms of direction of asymmetry. From the remaining qualitative correlations, higher coefficients were found between EVEROM and EVEINV (φ = 0.92, φr = 0.99) for the PTCF component, and between FLESTR and EXTSTR (φ = 0.57, φr = 0.78) for the PIKS component.

The categorical expressions of the functional asymmetry variables were subjected to correlational analyses with the variables reflecting the conventional aspects of lateral dominance. Overall, a clear qualitative (nonparametric) association between PTCF asymmetries and the conventional lateral dominance characteristics of the upper limbs (WH, DH, TH) was not observed.

With respect to lower limb dominance, only one significant qualitative correlation was found. Laterality in TOTROM correlated significantly with laterality in the kicking leg (KL, C = 0.54, p = 0.016). This correlation implied a significant trend of concordance (c = 28, %c = 71.4%) between the foot with the greater range of subtalar joint motion and the foot preferentially used to kick a soccer ball for distance, even though the subjects were not avid soccer players. Overall, there was not a distinct trend of association between PIKS asymmetries and the conventional characteristics of lateral dominance. An exception to this trend was the significant and negative correlations between FLEEXT and upper limb dominance (φ = -0.51, -c = 23, and %c = 79.3% for WH and DH, and φ = 0.43, -c = 21, and %c = 72.4% for TH).

Discussion of Results

Passive Talocalcaneal Flexibility Asymmetries

The mean values of the PTCF variables were similar to those found in previous studies (Brody, 1980; James et al., 1978; Warren, 1984). Particularly for TOTROM, a 30° range of motion in the subtalar joint is considered normal even though some asymptomatic runners exhibit only a 20° range of motion (Brody, 1980). Yet only a few studies have examined subtalar joint function with respect to asymmetry estimates. Warren (1984) reported mean static pronation asymmetry values, in favor of the right foot, for three groups of runners: 2.05° for a control group (24.8%), 1.66° for the plantar fasciitis group (29.3%), and 2.39° for the recovered-from-plantar-fasciitis group (31.4%).

Similar asymmetry data were also reported by Cavanagh et al. (1985) in a goniometric study of two elite distance runners. In the first runner the calcaneal
Table 3

Phi Correlation Coefficient ($\phi$) and Concordance (c) Matrices for the Nonparametric Interrelationships Between the Lateralizations of the Lower Limb Functional Asymmetries

<table>
<thead>
<tr>
<th></th>
<th>PTCF</th>
<th>PIKS</th>
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<tbody>
<tr>
<td></td>
<td>EVEROM</td>
<td>INVROM</td>
</tr>
<tr>
<td>EVEROM</td>
<td>-0.54***</td>
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<td>c</td>
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<tr>
<td>%c</td>
<td>03**</td>
<td>0.71</td>
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<tr>
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<tr>
<td>c</td>
<td>48</td>
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<tr>
<td>%c</td>
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<td>83**</td>
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<td>EVEINV</td>
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</tr>
<tr>
<td>FLEEXT</td>
<td>16</td>
<td>14</td>
</tr>
<tr>
<td>%c</td>
<td>55</td>
<td>55</td>
</tr>
</tbody>
</table>

*p ≤ 0.05; **p ≤ 0.01.

$\phi$ = phi correlation coefficients for dichotomous nominal data; $\phi r$ = corrected $\phi$ to be interpreted as Pearson's $r$.

$c$ = no. of positive or negative concordances between sides; $%c = c/N \times 100\%$ concordances between sides.

$\phi$ and $\phi r$ = above diagonal; c and $%c$ = below diagonal.
eversion and calcaneal angle were greater than normal on the right side. In the second runner all measurements were within normal limits, while the right foot exhibited 11° less inversion and 7° more eversion than the left. This tendency, of one foot to be more flexible in calcaneal eversion with the opposite foot being more flexible in calcaneal inversion, was also found in the present study (Table 1). The dominant (D) foot showed a greater range of eversion $(\text{Ma} = 4.04^\circ)$ while the nondominant foot (ND) showed a greater range of inversion $(\text{Ma} = -3.38^\circ)$.

In 22 subjects ($%c = 79\%$), EVEROM and INVROM asymmetries favored opposite sides. This produced a significant qualitative negative correlation of $\phi = -0.54 (\phi r = -0.74)$ between EVEROM and INVROM (Table 3). On the other hand, the sample was symmetric in the total range of motion (TOTROM) of the subtalar joint, while the proportions of these two variables to TOTROM were very asymmetric. EVEROM was 34% of TOTROM for the dominant foot and 21% of TOTROM for the nondominant foot. Thus it can be inferred that normal distance runners are symmetrical in the range of motion of the subtalar joint and inversely asymmetrical in eversion and inversion.

When EVEROM is expressed as a percentage of INVROM (EVEINV), an even more sensitive index of subtalar joint asymmetry is produced. Normal values for EVEINV have been reported by Brody (1980) to be between 0.50 and 0.33, which is similar to a value of 0.35, as calculated from the data reported by James et al. (1978). These values are comparable to those found in the present study (Table 1) where the dominant and nondominant foot presented EVEINV values of 0.52 and 0.27, respectively, translating to an asymmetry value of $\text{Ma} = 0.25 (\text{Ia} = 48.1\%)$ (Figure 3).

This finding may be of some value to the clinical assessment of the lower limbs of runners (James et al., 1978). Given the significant qualitative correlation $\phi = 0.92 (\phi r = 0.99, %c = 97\%)$ between EVEROM and EVEINV (Table 3), it can be proposed that static normalized eversion (EVEINV) be taken as a good predictor of functional subtalar joint problem during foot support. In theory, functional asymmetries and problems of this type are caused via compensatory mechanisms by asymmetries in the structure and flexibility of the feet (Gould, 1983; Mascie-Taylor et al., 1981), in the moment arms and forces acting upon the knee and ankle joints (McCure, Lee, Sahrmann, & Norton, 1985), and by leg length inequalities (Friberg, 1982; Klein, 1983; Subotnick, 1981).

**Peak Isokinetic Knee Strength Asymmetries**

In previous experimental studies investigating peak isokinetic knee strength in male subjects, mean asymmetries of different magnitudes were recorded, depending on whether asymmetry was directional (Gilliam et al., 1979; Goslin & Carteris, 1979; Pipes & Wilmore, 1975; Vandervoort, Sale, & Moroz, 1984) or fluctuating (Goslin & Carteris, 1979; Taunton et al., 1987; Wyatt & Edwards, 1981). For example, percent asymmetry values comparing the mean scores of the left and right sides were determined to be 1.6 to 5.02% (Pipes & Wilmore, 1975), 1.9% (Goslin & Carteris, 1979), and 2% (Gilliam et al., 1979) for the knee extension strength (EXTSTR), and 3% (Gilliam et al., 1979) for the knee flexion strength (FLESTR).

On average, these values were smaller than 5%, statistically insignificant, and therefore comparable to the percent directional asymmetries ($\text{Ia} < 2\%)$ of the
present study (Figure 3). Fluctuating asymmetries estimated in other research, on the other hand, presented the higher mean and percent values of 24.8 Nm (15.3%) (Goslin & Carteris, 1979), 16.26 Nm (8.9%) (Wyatt & Edwards, 1981), 14.91 Nm, and 13.55 Nm (7%) (Taunton et al., 1987) for the muscle strength of knee extension (EXTSTR), and 13.55 Nm (10.4%) (Wyatt & Edwards, 1981), 10.84 Nm (10%), and 6.78 Nm (5%) (Taunton et al., 1987) for the muscle strength of knee flexion.

In the present study, FLESTR and EXTSTR values were added and an estimate of the overall isokinetic strength (TOTSTR) of each leg was obtained (Tables 1 and 2, Figure 3). Even though similar indices are not reported in the literature, the 8.1% asymmetry determined for TOTSTR is similar to the percent asymmetry values presented above. With regard to the hamstring-to-quadriceps strength ratio (FLEEXT), the few studies that have examined isokinetic knee strength asymmetries did not report any asymmetry estimates for that parameter.

Overall, the results of the present and previous experimental studies seem to indicate that muscle strength asymmetries of as high as 10% are common in long-distance runners. Clinicians have expressed the opinion that these imbalances can be reduced to lower the risk of injury (Coplin, 1971; Knight, 1980). Whether this can be done, however, has not yet been supported by experimental evidence.

Strength asymmetries found in athletes are thought to be attributed to consistent asymmetries in the physical development of the segments, especially the muscles of the limbs (Damholt & Termansen, 1978; Mikkelsen, 1979; Singh, 1970). Another possibility concerns the systematic participation in unilateral sport activities, which in turn may invoke asymmetric neuromuscular adaptation in the form of asymmetrical distribution of fast and slow twitch motor units (Mikkelsen, 1979) or in the form of asymmetric motor unit activation (Vandervoort et al., 1984) in homologous muscle groups.

Strength asymmetries observed in athletes who are systematically involved in symmetric sports activities, such as swimming (Czabanski, 1975), cycling (Daly & Cavanagh, 1976; Rosenrot, 1980), sprinting (Vagenas & Hoshizaki, 1986), and distance running (Taunton et al., 1987; present study), cannot be easily interpreted. Particularly for ground locomotion, it has been theorized that most right-handed persons and almost all left-handed persons make greater use of the left lower limb for walking and transmission of the body (Singh, 1970), and that mediolateral balance is primarily controlled by the dominant leg (Matsusaka, Fujita, Kamamura, Norimatsu, & Suzuki, 1985). As a result this limb is forced into receiving higher mechanical loads, thus becoming better developed and stronger.

**Patterns of Functional Bilateralism**

The trends of conventional lateral dominance (preference) data of the subjects (Figure 6) were similar to those of other samples examined in previous investigations (Azemar, 1970; Singh, 1970; Vagenas & Hoshizaki, 1986; Zaichkowsky et al., 1980). The lack of general association between the functional lateralities (PTCF, PIKS) and the preferred dominance in the lower limbs was not surprising.

Previous data have indicated that the lateral preferences for kicking and jumping are not the best criteria for identifying the actual lateral dominance
trends of the lower extremities (Vagenas & Hoshizaki, 1986). In addition, the validity of the traditional entire limb dominance, as opposed to the more specific criteria of footedness (ankle) and leggedness (knee), is in doubt (Vanden-Abeele, 1980). This logic is supported by the finding that, despite an overall trend for the left side to be dominant in most cases (Figures 4 and 5), two distinct functional laterality components have emerged: one for the range of motion of the subtalar joint (PTCF) and one for the peak isokinetic knee flexion/extension muscle strength (PIKS).

These two joint-specific lateral dominances share some degree of dependence, as belonging to the same segmental system, while their mechanical functions are heterogeneous, thus leading to consistent but not identical laterality trends. Accordingly, it can be proposed that the lower limbs comply with joint-specific lateral trends rather than with a general state of total limb sidedness. Yet this laterality mechanism is primarily dependent on the specificity of the motor task, as determined by the degree of complexity of the movement and the type of joints involved.

On the other hand, the association between the normalized expression of flexion strength in the knee (FLEEXT) and the preferred hand for writing, drawing, and throwing (WH, DH, and TH, Table 4) again raised the problem of influence exerted by upper limb dominance upon the function of the lower limbs. A preliminary explanation of this finding was that the leg with the lesser strength imbalance between quadricep and hamstring muscles tends to be contralateral to the dominant hand. Since it is commonly accepted that upper limb dominance is more clearly defined and explained than lower limb dominance, its impact on the lateralization of knee function must not be totally excluded, even if the outcome of this process displays no clear-cut dependency between these two parameters.

Conclusions

1. The best mode of statistically estimating lateral differences is that of fluctuating asymmetry (D-ND), since the traditional directional (L-R) mode often leads to masking the actual asymmetries.
2. Long-distance runners exhibit significant asymmetries in the passive flexibility of the subtalar joint and in the muscle strength of the knee flexion/extension motion. For more accuracy, clinical or biomechanical assessments of the lower extremity function should be based on averaged repeated bilateral measures.
3. The laterality patterns of functional lower extremity asymmetries are consistent and in general independent of the conventional upper and lower limb dominance (lateral preferences).
4. The functional bilateralism of the lower extremities should be viewed as a joint- or task-specific phenomenon of the human body, and not as a general trend of lateral dominance for the entire limb.

References


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