Q-angle influences on the variability of lower extremity coordination during running

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ABSTRACT

HEIDERSCHEIT, B. C., J. HAMILL, and R. E. A. VAN EMMERIK. Q-angle influences on the variability of lower extremity coordination during running. *Med. Sci. Sports Exerc.*, Vol. 31, No. 9, pp. 1313–1319, 1999. The quadriceps angle (Q-angle) has received attention as a possible predictor of patellofemoral pain (PFP). It has been suggested that an excessive Q-angle alters the patellofemoral tracking, thereby leading to PFP. Traditional methods used to evaluate alterations in lower extremity angular kinematics have not confirmed this thought. A dynamical systems approach involving segment couplings may provide additional insight by addressing the variability of the intersegmental coordination. **Methods:** Thirty-two healthy pain-free subjects with varying Q-angles were examined and divided into groups based on gender and Q-angle. Subjects ran overground for 10 trials while three-dimensional kinematic data were collected from the thigh, leg, and foot. The kinematic data were digitized and filtered before a direct linear transformation was employed to calculate three-dimensional segment angles and angular velocities. The variability of the continuous relative phase (CRP) of segment couplings was used to assess between-trial consistency at specific stance phase intervals. **Results:** No differences in CRP variability were found among subjects with varying Q-angles. Significant differences were present between the specific intervals of the couplings with the greatest variability during initial stance ($P < 0.05$). **Conclusions:** A difference in CRP variability does not appear to exist in the lower extremity between individuals with and without abnormal Q-angles. The significant differences among the stance phase intervals of running suggest the inherent presence of coordination pattern variability. The importance of the increased pattern variability during initial stance may be associated with maintaining external stability. **Key Words:** PHASE PLOTS, CONTINUOUS RELATIVE PHASE, SEGMENT COUPLINGS

Alignment of lower extremity segments has often been implicated as a potential cause of running injury (4,13,18,19). With 25–30% of all knee injuries during running occurring at the patellofemoral joint (16), the orientation of the thigh, leg, and foot has been suggested to predispose individuals to patellofemoral pain (PFP). Various static goniometric measures have been defined to quantify the segmental alignment.

One particular lower extremity measure that has received attention as a possible predictor of PFP is the quadriceps angle (Q-angle). It is defined by the intersection of the lines connecting the anterior superior iliac spine (ASIS) to the center of the patella and from the center of the patella to the tibial tuberosity (Fig. 1). The Q-angle can be measured reliably (3,10), and it provides a reasonable estimate of the angle of the quadriceps muscles' pull on the patella in the frontal plane (11,12,22).

The proposed mechanism by which the Q-angle contributes to PFP involves a combination of lower extremity segments (25). A large Q-angle magnitude has been suggested to produce excessive foot pronation or rearfoot eversion. The increased foot eversion could then cause increased leg internal rotation with opposing femoral external rotation, thereby altering the patellofemoral tracking relation and possibly leading to a pain syndrome. Previous investigations into the kinematics associated with running injuries have focused typically on angular events of one or more lower extremity segments, such as maximum rearfoot angle and maximum leg internal rotation (8,18,24). Stergiou et al. (24) investigated the association between tibial rotation and PFP among subjects with varying Q-angles by measuring the maximum internal tibial rotation during stance. The authors concluded that tibial rotation was not different among groups. By limiting the analysis to discrete segment angles,

0195-9131/99/3109-1313/0
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Submitted for publication March 1998.
Accepted for publication October 1998.

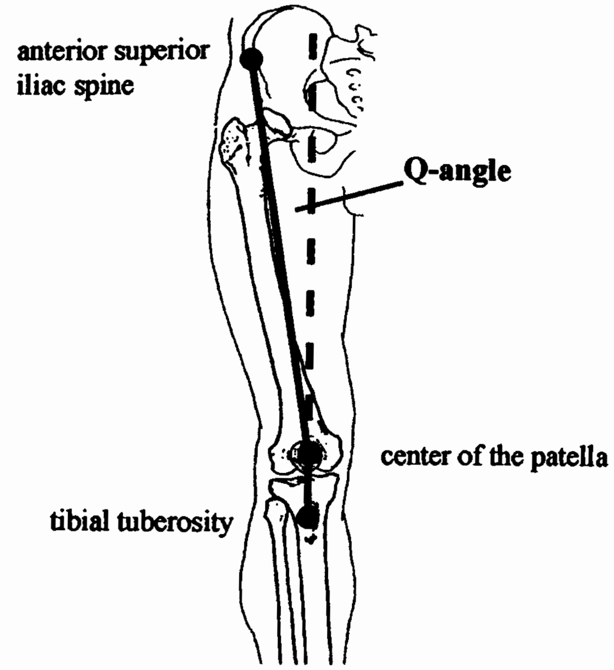

Figure 1—Q-angle defined by the intersection of quadriceps vector and infrapatellar tendon at center of patella.

one would conclude the Q-angle to have minimal effect on altering lower extremity kinematics during running.

McClay and Manal (18) investigated lower extremity segment mechanics between subjects with normal rearfoot motion and those who display excessive pronation by measuring coupled segment parameters. Excursion ratios between rearfoot eversion and tibial internal rotation were measured, as well as the relative timing of peak eversion, knee flexion, and knee internal rotation. No significant group differences were present for the timings between peak knee and rearfoot angles. The eversion to tibial internal rotation excursion ratio, however, was lower among the subjects with excessive pronation. By coupling segment motion, additional insight into group kinematic differences was provided. However, again the coupling analysis was limited to a discrete measure (i.e., peak events). The relation between the tibia and foot segments during the remaining portions of stance is not known.

While providing information on the individual segment movements, discrete measures as previously described will not address segment kinematic coordination throughout the stance phase of locomotion. To assess segment coordination, the relative phase between segments has been described as an appropriate variable to measure (6,14,28).

Relative phase refers to the angular phase relations between two segments and represents cooperation between the segments (15,29). It can therefore be considered a reflection of the system's coordination pattern (28). The angular phase relation is derived from phase plane analyses that include angular position and velocity (see Fig. 2 for details). By measuring the relative phase over the entire time period, continuous relative phase (CRP) provides an assessment of segmental coupling throughout the entire stance or stride phase.

Van Emmerik and Wagenaar (28) used CRP to demonstrate a systematic change in pelvic-thoracic coupling from in-phase to more out-of-phase as walking velocity was increased. In-phase is defined as having a CRP of 0°, while antiphase is 180°. In addition, the variability of the movement pattern increased at specific velocities, indicating a loss of the stability of the coordination between the pelvis and thorax.

Pattern stability is defined by the ability of the system to maintain a pattern or return to a pattern through a variety of perturbations including changes in a control parameter, such as velocity of locomotion (15). When discussing segment coordination, stability can be measured by calculating the variability of the CRP pattern (6). Low CRP variability would indicate a rigid, stable pattern, while high CRP variability would suggest a more flexible or potentially unstable pattern (28).

The presence of variability has been suggested to indicate a coordination change. Kelso (14) investigated finger oscillation patterns as movement frequency was increased and detected a distinct shift in the relative phase from an antiphase to in-phase pattern at a critical frequency. This transition was marked by an increase in relative phase variability, indicating that antiphase pattern became unstable. Kelso (14) concluded that the variability is an intricate component to coordination change. In addition, transition problems during locomotion in Parkinson's disease patients have been linked to a reduced variability in coordination patterns (29), suggesting that coordination variability is involved with locomotion adaptability.

The phase relations of three different segment couplings are of interest in assessing the influence of the Q-angle on the variability of lower extremity coordination. First, based on the segments that define the Q-angle, the magnitude of thigh abduction/adduction and leg rotation may be altered. The potential also thereby exists for the dynamic relations of these two segments to be changed. Second, when considering the speculations of Subotnick (25) regarding the possi-

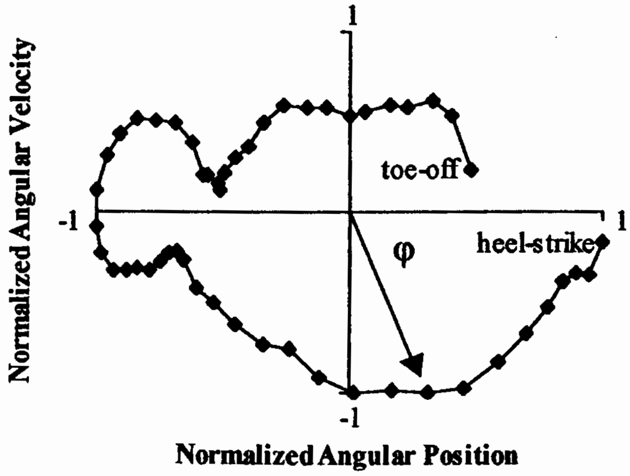

Figure 2—Sample phase plot of foot eversion/inversion from an exemplar subject during a single trial following the normalization process. The phase angle (φ) is calculated from the angle between the right horizontal and a line drawn from the origin to a specific data point.

bility of high Q-angles producing increased foot pronation, one should consider leg rotation and foot eversion/inversion. Finally, thigh flexion/extension and leg rotation may be altered based on the data from Hamill et al. (8) and Tiberio (26). Both investigators speculated that a shift in timing between maximum leg internal rotation and maximum knee flexion occurs as a result of increased pronation. Changes in this pattern may produce increased tibial torque, eventually producing PFP. While other possible interactions exist, investigation into the above three segment couplings was emphasized.

The purpose of this study was to examine the influence of the Q-angle on the variability of lower extremity segment coordination during running. The presence of altered CRP variability in the lower extremity segments' coordination patterns among individuals with an abnormal Q-angle would indicate the Q-angle magnitude to have an influence on running kinematics.

METHODS

Subject selection. Sixteen males and 16 females were selected from the University of Massachusetts community. Appropriate sample size was estimated using Cohen Case 0 for a minimum statistical power of 80% (5). Each participant was required to read and sign a written informed consent approved by the human subjects committee of the University of Massachusetts, as well as complete and sign a participation questionnaire to verify health status. Inclusion was dependent on the following criteria: 1) no history of lower extremity injury within the last 10 yr; 2) no use of orthotics; and 3) less than 1.27-cm difference between lengths of the right and left lower extremities since a larger difference may alter the maximum eversion angle or its derivative (8,26). Measured Q-angle and gender were used as criteria for dividing the subject sample into four groups of eight subjects each. Based on the findings of Messier et al. (19), abnormal Q-angles were defined as greater then 15°. In addition, Q-angle differences exist between genders (10,24), thereby suggesting potential gender effects on segment couplings. The males ranged in age from 19 to 32 yr (22 ± 3), in body mass from 55.5 to 89.0 kg (73.2 ± 9.8), and in height from 162.5 to 188.0 cm (176.3 ± 6.3). The females ranged in age from 19 to 32 yr (23 ± 3), in body mass from 48.0 to 72.5 kg (57.6 ± 5.82), and in height from 150.0 to 171.0 cm (161.3 ± 5.5). No statistically significant differences within gender were present between Q-angle groups for age, mass, or height, while the mass and height displayed significant differences across gender ($P < 0.001$).

Experimental set-up. Kinematic data were collected using two high-speed (200 Hz) video cameras and recorders (NAC, Burbank, CA). A triad of three noncollinear markers was securely placed on the lateral surface of the right thigh, leg, and foot. The room coordinate system was defined using a 1-m cube containing 25 markers of known coordinates. Foot-ground contact was indicated by an illuminated light-emitting diode (LED) interfaced with the vertical ground reaction force component from a force platform located flush with the running surface (Advanced Mechanical Technologies, Inc., Newton, MA). The LED was placed in view of both cameras. Subject velocity was monitored via photoelectric sensors interfaced with a digital counter and placed on either side of the force platform at a known distance from each other.

Protocol. A comprehensive lower extremity evaluation was performed on each subject by the same physical therapist. All goniometric measures were recorded from the right lower extremity in a weight-bearing position. In addition to the Q-angle, genu valgum and tibial varum were recorded. Excessive values of genu valgum or tibial varum have been suggested to influence the gait pattern, possibly producing group differences in kinematics (8). With a tape measure, the existence of a lower extremity length discrepancy was also determined (17); a bilateral difference of greater than 1.27 cm prevented subject participation.

Male subjects ran at a velocity of 3.83 $m \cdot s^{-1}$ ± 5.0% across the force platform while females ran at a velocity of 3.6 $m \cdot s^{-1}$ ± 5.0%. The difference in running velocity was in regard to the inherent running velocity difference present between genders (2). In an attempt to control for extraneous segment movements, all subjects wore running shoes with a standardized midsole durometer (8). Subjects were also instructed not to target the force platform with their right foot as forced kinematic changes may result. A total of 10 trials were recorded for each subject with a trial deemed acceptable if velocity was maintained within the specified range and the entire right foot contacted the force platform. Finally, as a reference for the running trials, a static calibration trial was recorded of each subject such that the long axis of the foot was aligned in the sagittal plane with the subject standing in full knee extension.

Data reduction. The Motion Analysis VP 110 Expert Vision System (Motion Analysis Corp., Santa Rosa, CA) interfaced to a microcomputer was used to digitize the stance phase of the kinematic data. The illuminated LED indicated the stance phase, defined as right foot heel-strike to toe-off. The digitized data produced the Cartesian coordinates (x, y) of each marker at each frame during the stance phase. Three additional frames before heel-strike and after toe-off were included in the analysis to minimize filtering effects. Higher frequencies associated with noise were eliminated using a 16 Hz low-pass 4th order zero lag Butterworth filter. The frequency cutoff was determined based on power spectral densities of the x and y marker paths of each segment and selecting a common frequency that contained 95% of the power.

A direct linear transformation was employed to reconstruct the three-dimensional image from the x and y coordinates collected from the right and left cameras (23). A local coordinate system was calculated from the triads on each segment throughout the stance phase and oriented to the calibration position of the respective subject (1). Three-dimensional segment angles were calculated as described by Areblad et al. (1), and three-dimensional joint angles were calculated according to a method specified by Grood and Suntay (7).

Phase plots of the relevant components for the foot, leg, and thigh were used to compare lower extremity segment coordination during running. These components included thigh adduction/abduction, thigh flexion/extension, leg rotation, and foot eversion/inversion. Each phase plot consisted of the segment angle on the horizontal axis with its first derivative, angular velocity, on the vertical axis. Segment angles were normalized resulting in the midpoint at 0 and the maximum and minimum values being 1 and −1, respectively. The angular velocity data were normalized to their maximum absolute value to maintain the zero velocity at the origin. The normalization process minimized the influence of different amplitudes in the calculation of the phase angles. The phase angle was defined as the angle between the right horizontal and a line drawn from the origin to a specific data point with the resulting phase angle range being 0–180°.

The CRP was defined as the difference between the normalized phase angles of two segment motions throughout the stance phase. The CRP was calculated from the normalized phase plots for three pairs of kinematic variables: 1) thigh flexion/extension and leg rotation, 2) thigh abduction/adduction and leg rotation, and 3) leg rotation and foot eversion/inversion. The phase angle of the distal segment of each coupling was subtracted from the proximal segment's phase angle at each point in the stance phase.

With the use of a linear interpolation technique, each CRP curve was rescaled to a percent of the stance phase. An ensemble curve, indicating the mean of the 10 rescaled CRP curves, was calculated for each segment coupling of each subject. The variation of CRP was calculated as the standard deviation of the 10 trials at each percent of stance on the ensemble curve. Thus, the standard deviation represents the between-trial variability.

To provide a more detailed analysis, the ensemble curves were divided into four intervals based on specific stance phase events. The spatial angle events of foot eversion/inversion were used to define the intervals over which the mean CRP was calculated (Fig. 3).

In an attempt to quantify each interval, mean values for CRP variability were calculated using equation 1. This single representative value provided comparison of the variability curves between subjects.

$$\text{Mean CRP variability} = (\Sigma|\text{CRP variability}_{(i)}|)/n \qquad (1)$$

where i = each point in the interval and n = the total number of points in the interval.

Statistical analysis. To determine the presence of a gender effect, two-way ANOVA (gender by Q-angle group) were conducted on the means of the four CRP variability intervals, as well as the goniometric measures. Because no significant gender effects or interactions existed for the CRP variability measures (see *Results*), the remaining statistical analyses were performed with the original four groups collapsed across gender into two groups: Q-angle > 15° and Q-angle ≤ 15°. The means of the four CRP variability intervals were analyzed using a two-way ANOVA (groups by intervals) across groups. *Post-hoc* analyses of the ANOVA were performed using Scheffe test. The previous analyses were conducted on each of the coupled segments.

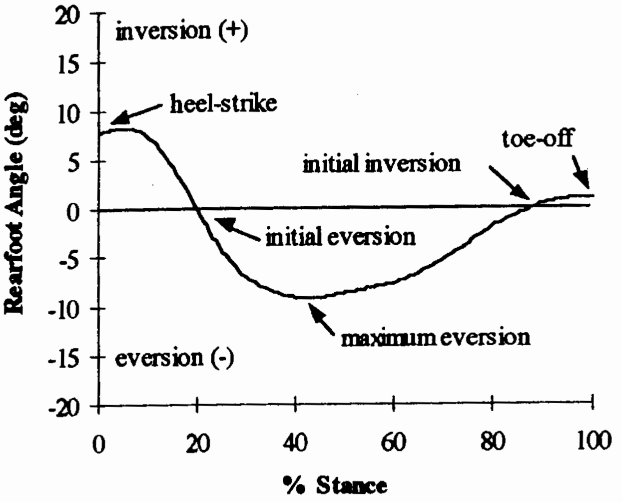

Figure 3—Foot eversion/inversion angles during a single stance phase for an exemplar subject. Four intervals were defined as follows: 1) heel-strike to initial foot eversion, 2) initial foot eversion to maximum foot eversion, 3) maximum foot eversion to initial foot inversion and 4) initial foot inversion to toe-off.

RESULTS

No significant differences were found between genders for any of the CRP coupling variables ($P > 0.15$), thus justifying the collapse of the original four groups into two groups, low Q-angle (LQ) and high Q-angle (HQ). The measured Q-angle, however, was significantly different between groups ($P < 0.05$; Table 1), while no group differences were present for the other static goniometric measures, genu valgum ($P > 0.70$), and tibial varum ($P > 0.60$).

A sample phase plot of foot eversion/inversion during stance phase of running is shown in Figure 2. The direction of motion for the phase plots of all segment couplings was clockwise. The discontinuity present in the phase plot was a result of the analysis being performed only over the stance phase of running. An enclosed continuous plot would be present had the entire stride cycle been analyzed.

Mean CRP variability for the LQ and HQ groups throughout the stance phase are displayed in Figure 4. All segment couplings are presented.

No significant differences existed between high and low Q-angle groups for the CRP variability of any segment couplings ($P > 0.15$; Table 2). However, significant CRP variability differences were found between the stance intervals of all segment couplings ($P < 0.05$).

Table 3 displays the CRP variability mean and SD of the LQ and HQ groups for each segment coupling. Based on the *post-hoc* tests, both thigh flexion/extension with leg rotation and thigh adduction/abduction with leg rotation displayed significantly higher CRP variability values during the initial stance phase (i.e., from heel-strike to initial eversion) than the remainder of stance ($P < 0.001$). The remaining intervals for the two couplings were similar. The leg rotation

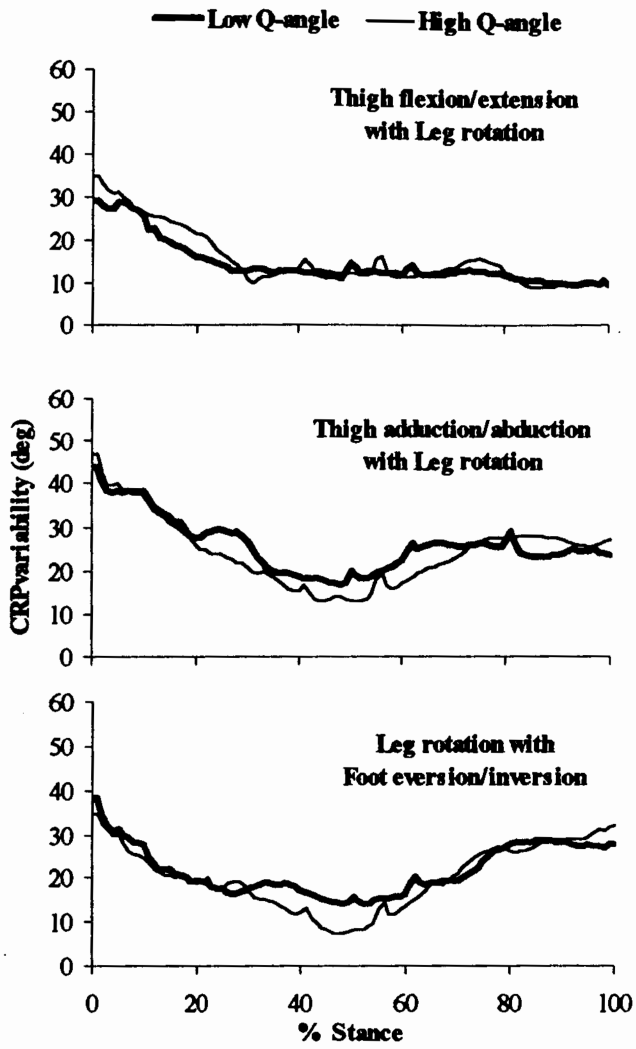

Figure 4—Mean variability of continuous relative phases (CRP) for all lower extremity segment couplings throughout the stance phase for the low and high Q-angle groups.

with foot eversion/inversion CRP variability values for the initial two intervals were significantly different from each other ($P < 0.05$) but not from the remaining intervals.

Figure 5 displays the means of the CRP variability pooled across groups for each interval of the segment couplings. The CRP variability for all couplings was highest during initial foot contact, heel-strike to eversion. For thigh flexion/extension with leg rotation and thigh adduction/abduction with leg rotation, the CRP variability progressively decreased throughout the remainder of stance. Leg rotation with foot eversion/inversion, however, displayed a return to higher variability at the end of stance.

DISCUSSION

The presence of altered CRP variability in the lower extremity segments' coordination patterns between the LQ and HQ groups would indicate that the Q-angle magnitude had an influence on running kinematics. However, none of the segment couplings investigated revealed this between-group alteration in pattern variability. The lack of significant group differences for thigh flexion/extension with leg rotation and thigh adduction/abduction with leg rotation suggests that the Q-angle does not affect the coordination variability of the segments that define it.

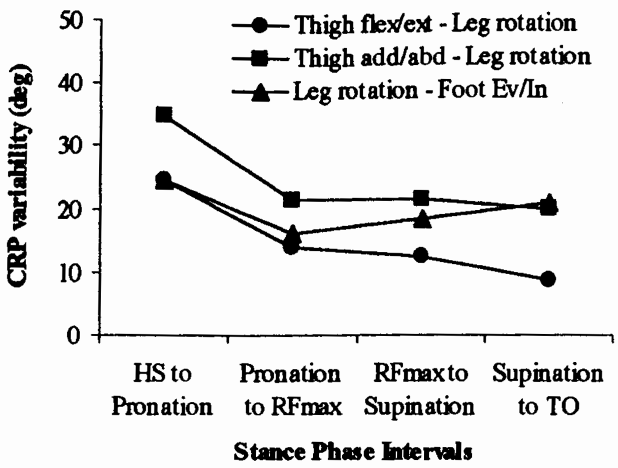

Figure 5—Mean values of continuous relative phase (CRP) variability at each stance phase interval for the coupled segments of all subjects pooled across groups. HS, heel-strike; TO, toe-off; RF_{max}, maximum eversion.

As stated in the introduction, Subotnick (24) proposed high Q-angles produced an increase in leg rotation and foot eversion. The results of this investigation revealed no group difference in CRP variability for leg rotation with foot eversion/inversion. Therefore, the effect of Q-angle on the coordination variability of leg rotation or foot eversion is not apparent. It should be noted, however, that while no significant CRP variability differences were present between groups, the HQ group consistently showed greater CRP variability values for all stance intervals of each coupling (Table 3).

The lack of significant group differences present in all three couplings suggests that a coordination variability change is not present in the lower extremity between individuals with and without abnormal Q-angles. This indicates the consistency of the lower extremity coordination pattern to be similar regardless of the Q-angle magnitude. Although the static lower extremity alignment was different between groups, the kinematic relations between lower extremity segments during running were consistent. The investigation, however, did reveal distinct CRP variability phases during running for all subjects involved.

The significant differences found between the stance phase intervals of the coupled segments suggest the presence of a consistent shift in the running coordination pattern during a single stance phase. The mean group values displayed in Table 3 indicate that all the coupled segments' patterns have the greatest variability during the initial period

TABLE 1. Goniometric measures (°) of the right lower extremity.

Angle	LQ	HQ	*P*-Value
Q-angle	11.8 ± 1.8	18.4 ± 2.5	0.04*
Genu valgum	6.8 ± 2.4	6.5 ± 2.6	0.78
Tibial varum	5.1 ± 1.5	5.3 ± 1.4	0.65

* $P < 0.05$. Data are expressed as mean ± SD.

TABLE 2. ANOVA results for the continuous relative phase (CRP) variability of the stance phase intervals for each of the coupled segments.

CRP Variability	Group	Interval	Group × Interval
Thigh flexion/extension with leg rotation	0.06 (0.82)	17.15 (<0.01*)	0.13 (0.94)
Thigh adduction/abduction with leg rotation	0.28 (0.60)	12.38 (<0.01*)	1.61 (0.19)
Leg rotation with foot eversion/inversion	1.90 (0.18)	2.99 (0.03*)	0.56 (0.64)

* $P < 0.05$. Data are expressed as F-value (P-value).

of stance, from heel-strike to initial. Figure 4 further illustrates this observation. The presence of the increased CRP variability only at the beginning of stance suggests that this is not a filtering artifact. With these data, increased variability would be expected at the beginning and end of stance if insufficient padding during the filtering process were responsible.

After determining the variability to be true, explanations for its presence need to be addressed. While a highly stable pattern can minimize metabolic cost (9), it may lack the ability to adapt to system perturbations. The presence of variability offers the system the flexibility to overcome these perturbations. Turvey (27) suggested that a balance between system stability and variability might be required for optimal performance. The predominance of one may limit the system by increasing the risk of falling or increasing the metabolic costs, respectively.

Previous investigators using the dynamical systems approach have suggested that variability exists to allow exploration of the possible coordination patterns (20,21). As skill is acquired, the variability is decreased because of the system's selection of an optimal pattern. However, Holt et al. (9) demonstrated that the lower extremity joint patterns possess a degree of variability during walking, with the distal joints being most variable. They argued that the distal joint variability was needed to minimize the ground impacts and to provide an adaptive mechanism to potential external perturbations.

The current findings not only support Holt et al. (9) but also provide further details of the variability and stability relation during the stance phase of running. The increased variability consistently found between coupled segments at heel-strike indicates a flexible system. This allows the system to explore its environment, in this case the ground surface, to maintain external stability. If a stable pattern is present at heel-strike, the ability of the system to recover from a perturbation may be limited, resulting in the individual falling or a loss of external stability. Once the surface is known, a stable pattern can then present itself without compromising the external stability. This association may provide for an adequate balance between pattern stability and variability without limiting performance. The lack of significant group differences indicate this balance to be unaffected by excessive Q-angles.

The variability of the pattern at heel-strike suggests that it is present during terminal swing as a possible anticipation mechanism for stance. The presence of variability before the mechanical stimulus of heel-strike would imply an additional control mechanism anticipating foot-ground contact. Future investigations concerning the variability of lower extremity segment coordination need to be conducted over the entire stride cycle to confirm this notion.

As suggested by Holt et al. (9), increased CRP variability may also be functionally necessary to augment the large impact shock present during foot-ground contact. A highly stable pattern would result in the same anatomical surfaces receiving the impact shock repeatedly. A variable pattern would allow for the impact to be imparted to various structures, potentially avoiding future injury from repetitive strain. The CRP during initial stance, heel-strike to initial eversion, was consistently more variable than the other intervals for all couplings, providing support to this explanation.

The lack of group differences revealed in this investigation may be a reflection of the subjects involved. The selection of healthy subjects was appropriate to test the effect of the Q-angle on coordination; however, these results cannot be generalized to subjects with lower extremity pathologies. Coordination differences may exist between subjects with and without lower extremity injury. Future investigations involving individuals with lower extremity injuries need to be initiated to identify potential alterations in segment coordination.

In an attempt to determine the effect of Q-angle magnitude on the coordination of lower extremity segments, relative phase and its variability were calculated from various coupled segment motions. The lower extremity segment couplings displayed similar CRP variability for both the HQ and LQ groups, indicating the Q-angle to have no influence on coordination pattern variability. Furthermore, all subjects revealed distinct CRP variability phases during running. Early stance phase consistently displayed greater variability

TABLE 3. Continuous relative phase (CRP) variability values (°) for each of the couplings calculated over the entire stance phase and the four intervals within the stance phase.

	Thigh Flex/Ext & Leg Rot		Thigh Add/Abd & Leg Rot		Leg Rot & Foot Ev/In	
Interval	LQ	HQ	LQ	HQ	LQ	HQ
Stance	14.3 ± 10.6	15.6 ± 7.1	22.1 ± 8.8	27.9 ± 11.8	17.7 ± 6.3	24.3 ± 7.1
1	24.9 ± 17.3	29.5 ± 10.4	36.0 ± 12.8	40.6 ± 11.7	24.6 ± 8.6	30.1 ± 7.6
2	13.7 ± 12.4	14.2 ± 9.5	19.9 ± 10.9	23.0 ± 12.6	15.1 ± 9.5	17.2 ± 6.3
3	12.5 ± 14.6	12.6 ± 10.8	17.7 ± 10.7	25.2 ± 13.2	14.7 ± 9.4	22.1 ± 11.2
4	9.3 ± 3.3	12.6 ± 7.0	23.5 ± 11.8	25.5 ± 17.4	22.3 ± 12.7	30.2 ± 17.1

Data are expressed as mean ± SD.

flex/ext, flexion/extension; add/abd, adduction/abduction; ev/in, eversion/inversion; rot, rotation. Intervals: 1, heel-strike to initial eversion; 2, initial eversion to maximum eversion; 3, maximum eversion to inversion; 4, inversion to toe-off.

than the remaining stance. The significance of the increased pattern variability during initial stance may be associated with maintaining external stability. Additional investigations should be conducted to verify these conclusions.

The authors thank Dr. Graham E. Caldwell for his critical review of the study proposal and assistance with the manuscript preparation.

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REFERENCES

1. Areblad, M., B. M. Nigg, J. Ekstrand, K. O. Olsson, and H. Ekstrom. Three-dimensional measurement of rearfoot motion during running. *J. Biomech.* 23:933–940, 1990.
2. Bhambhani, Y. and M. Singh. Metabolic and cinematographic analysis of walking and running in men and women. *Med. Sci. Sports Exerc.* 17:131–137, 1985.
3. Caylor, D., R. Fites, and T. W. Worrell. The relationship between quadriceps angle and anterior knee pain syndrome. *J. Orthop. Sports Phys. Ther.* 17:11–16, 1993.
4. Clarke, T. E., E. C. Frederick, and C. T. Hamill. The study of rearfoot movement in running. In: *Sports Shoes and Playing Surfaces: Biomechanical Properties,* E. C. Frederick (Ed.). Champaign, IL: Human Kinetics, 1984, pp. 451–456.
5. Cohen, J. *Statistical Power Analysis for the Behavioral Sciences.* Hillsdale, NJ: Erlbaum, 1977, pp. 27, 40–42.
6. Diedrich, F. J. and W. H. Warren. Why change gaits? Dynamics of the walk-run transition. *J. Exp. Psychol.: Hum. Percept. Perform.* 21:183–202, 1995.
7. Grood, E. S. and W. J. Suntay. A joint coordinate system for the clinical description of three-dimensional motions: application to the knee. *J. Biomech. Eng.* 105:136–144, 1983.
8. Hamill, J., B. T. Bates, and K. G. Holt. Timing of lower extremity joint actions during treadmill running. *Med. Sci. Sports Exerc.* 24:807–813, 1992.
9. Holt, K. G., S. F. Jeng, R. Ratcliffe, and J. Hamill. Energetic cost and stability during human walking at the preferred stride frequency. *J. Mot. Behav.* 27:164–178, 1995.
10. Horton, M. G. and T. L. Hall. Quadriceps femoris muscle angle: normal values and relationships with gender and selected skeletal measures. *Phys. Ther.* 69:897–901, 1989.
11. Huberti, H. H. and W. C. Hayes. Patellofemoral contact pressures: the influence of Q-angle and tendofemoral contact. *J. Bone Joint Surg.* 66A:715–724, 1984.
12. Insall, J. N., K. A. Falvo, and D. W. Wise. Chondromalacia patellae: a prospective study. *J. Bone Joint Surg.* 58A:1–8, 1976.
13. James, S. L., B. T. Bates, and L. R. Osternig. Injuries to runners. *Am. J. Sports Med.* 6:40–50, 1978.
14. Kelso, J. A. S. Phase transitions and critical behavior in bimanual coordination. *Am. J. Physiol: Regul., Integr., Comp. Physiol.* 15: R1000–R1004, 1984.
15. Kelso, J. A. S. *Dynamic Patterns: The Self-organization of Brain and Behavior.* Cambridge, MA: MIT Press, 1995, pp. 5–8, 79–81.
16. MacIntyre, J. G., J. E. Taunton, D. B. Clement, D. R. Lloyd-Smith, D. C. McKenzie, and R. W. Morrell. Running injuries: a clinical study of 4,173 cases. *Clin. J. Sports Med.* 1:81–87, 1991.
17. Magee, D. J. *Orthopedic Physical Assessment.* Philadelphia: W. B. Saunders Company, 1987, p. 267.
18. McClay, I. and K. Manal. Coupling parameters in runners with normal and excessive pronation. *J. Appl. Biomech.* 13:109–124, 1997.
19. Messier, S. P., S. E. Davis, W. W. Curl, R. B. Lowery, and R. J. Pack. Etiologic factors associated with patellofemoral pain in runners. *Med. Sci. Sports Exerc.* 23:1008–1015, 1991.
20. Schmidt, R. C., P. J. Treffner, B. K. Shaw, and M. T. Turvey. Dynamical aspects of learning and interlimb rhythmic movement pattern. *J. Mot. Behav.* 24:67–83, 1992.
21. Schöner, G., P. G. Zanone, and J. A. S. Kelso. Learning as change of coordination dynamics: theory and experiment. *J. Mot. Behav.* 24:29–48, 1992.
22. Schulthies, S. S., R. S. Francis, A. G. Fisher, and K. M. van De Graaff. Does the Q-angle reflect the force on the patella in the frontal plane? *Phys. Ther.* 75:30–36, 1995.
23. Shapiro, R. Direct linear transformation method for three-dimensional cinematography. *Res. Q.* 49:197–205, 1978.
24. Stergiou, P., B. M. Nigg, P. J. Wiley, and N. G. Mohtadi. Tibial rotation, Q-angle and its association to PFPS in runners. In: *Proceedings, Ninth Biennial Conference, Canadian Society for Biomechanics.* Vancouver, B.C.: Canadian Society for Biomechanics, 1996, pp. 138,139.
25. Subotnick, S. I. Orthotic foot control and the overuse syndrome. *Physician Sportsmed.* 3:32–38, 1975.
26. Tiberio, D. Effect of excessive subtalar joint pronation on patellofemoral mechanics: a theoretical model. *J. Orthop. Sports Phys. Ther.* 9:160–165, 1987.
27. Turvey, M. T. Coordination. *Am. Psychol.* 45:938–953, 1990.
28. Van Emmerik, R. E. A. and R. C. Wagenaar. Effects of walking velocity on relative phase dynamics in the trunk in human walking. *J. Biomech.* 29:1175–1184, 1996.
29. Wagenaar, R. C. and R. E. A. van Emmerik. Dynamics of pathological gait. *Hum. Mov. Sci.* 13:441–471, 1994.