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Research Article

Lower-Limb Coordination Responses to Knee Bracing in Females with Anterior Knee Pain

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Abstract

Background: Anterior Knee Pain (AKP) during running has been partially attributed to lower-limb kinematics. Mechanical deviances from asymptomatic cohorts at the hip, knee, shank and foot have been reported for joints and segments in isolation. Appraisal of lower-limb coordination and its variability may provide important insight into the role of proximal and distal lower-limb joint and segment couplings during running with AKP. The extent to which current knee bracing strategies (standard-fit and custom-fit) for pain moderation influence lower-limb couplings may assist in the development of empirically informed recommendations for AKP management. The aim of this study was to investigate lower-extremity kinematic couplings of AKP participants during running without bracing and when wearing standard- and custom-fit knee braces.

Methods: Eighteen females (nine AKP, nine asymptomatic) performed ten running trials at a fixed speed (3.2 $m \cdot s^{-1}$) in a custom-fit knee brace, a standard-fit knee brace and no brace. Three-dimensional unilateral lower-limb kinematics data were obtained from which, joint and segment angles were calculated. Hip-knee, knee-ankle, thigh-shank and shank-foot coordination and coordination variability were determined using a modified vector coding technique.

Results: AKP participants spent less time in knee internal rotation-dominant couplings ($P < 0.05$) and a greater proportion of stance in ankle eversion-dominant couplings ($P = 0.01$; ES = 0.62). Frontal plane hip-knee couplings were found to differ for AKP participants when wearing standard- and custom-fit braces ($P = 0.04$; ES = 0.39). Overall, bracing conditions had the greatest influence on the asymptomatic cohort. No coordination variability differences were found between groups or conditions.

Discussion: Participants with AKP ran with different lower-limb coordination strategies than their asymptomatic counterparts. Localized joint bracing (standard- and custom-fit) did not oppose the coupling mechanics found in the AKP cohort when running in the unconstrained condition. It is therefore suggested that pain management strategies which consider the whole limb may be more effective than knee braces alone.

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Keywords: Coordination Variability; Joint Coordination; Running; Segment Coordination; Vector Coding

Introduction

Anterior Knee Pain (AKP) is a common manifestation of Patellofemoral Pain Syndrome (PFPS) for which incidence rates have been documented to be 2.23 times greater for females than males [1]. Typically aggravated by increased patellofemoral joint compressive force, AKP primarily occurs during repetitive locomotor activities such as running [2]. The high prevalence of AKP in active populations are reported to be partially attributed to intrinsic biomechanical mechanisms including lower extremity malalignment, muscular imbalance and abnormal movement patterns [3].

A wealth of research has been dedicated to further understand the altered joint and segment kinematics strategies used by AKP cohorts during running. Biomechanical insight has exposed the multi-segmental nature of AKP development through its associations with hip, knee, shank and foot mechanics [4-9]. However, conflicting evidence has resulted from the analyses of isolated joint and segment mechanics, indicating the potential benefit of adopting an approach which considers the interaction of joints and segments in furthering understanding of AKP mechanics during running.

A dynamical systems approach to appraise the interaction of individual degrees of freedom in accordance with Bernstein's principles [10] is anticipated to expose valuable insight which may be masked by isolated joint and segment analyses. The coordination of adjacent joints during a movement pattern has etiological associations with injury [11], whereas inter-segmental coupling may offer advanced understanding on the control of multiple degrees of freedom to achieve individual joint motion. Initial insight into lower-limb couplings of PFPS cohorts have revealed shank-rearfoot [12], shank-knee [13] and knee-rearfoot [13] differences with asymptomatic cohorts during running. Understanding of proximal lower-limb couplings inclusive of the thigh segment and hip joint in addition to distal ankle coupling strategies may assist the advancement of pain management, prevention and rehabilitation strategies for individuals with AKP.

Within asymptomatic individuals, joint and segment coordination variability enables stable structures to move with sufficient flexibility for adaptation to perturbations [14]. Lower levels of joint and segment coordination variability throughout locomotion indicate the potential for overuse injury risk development due to repetitive stress on consistent structures [14,15]. As has been shown through the exploration of inter-segmental variability [14], understanding of the variability of joint and segment coordination during locomotion may expose underlying contributing mechanisms to AKP

With the aim of correcting biomechanical deficits that may contribute to pain, knee bracing is a low-cost resource which can be worn during locomotion activities. In addition to pain reduction, a primary purpose of the knee brace is to promote joint stability [16] for which, a well-fitting knee orthosis is crucial. Different types of knee-braces can be broadly categorized as standard-fit (offered in limited sizes) and custom-fit (tailored fit using anthropometric measures). Altered lower-limb kinematics have been reported with the use of a hinged knee brace, including reductions of peak hip and knee flexion during running [17]. Understanding the influence of knee brace design on inter-joint and inter-segmental movement patterns may be advantageous in directing the focus of AKP management and prevention strategies (e.g. the extent to which multiple joints should be considered). Bracing is predominantly used to support painful or injured joints but can also be used as an injury prevention strategy for healthy cohorts. The distinct roles of knee bracing between populations are indicative of the need for braces to have a greater biomechanical influence on symptomatic populations (e.g. AKP), with reduced biomechanical influence on asymptomatic individuals.

Therefore, the aim of this study was to investigate lower-extremity kinematic couplings of AKP participants during running without bracing and when wearing standard- and custom-fit knee braces. Based on previous biomechanical analyses of independent and coupled lower-limb joints and segments, it was hypothesized that runners with AKP would utilize different coupling patterns and have lower coordination variability than their asymptomatic counterparts. As modification of functional joint stability is a primary objective of knee bracing, it was further hypothesized that the AKP cohort would have different coordination and coordination variability responses to standard-fit, custom-fit and no brace conditions, while knee bracing would have no significant effect on coupling mechanisms in the asymptomatic cohort.

Methods

Participants

Eighteen habitual female rearfoot runners participated in this study (nine asymptomatic and nine AKP). The asymptomatic group had a mean age, height and mass of 22.1 ± 2.6 years, 1.67 ± 0.07 m and 58.6 ± 7.3 kg, respectively. The mean age, height and mass for the AKP group was 22.7 ± 6.0 years, 1.69 ± 0.08 m and 62.0 ± 8.8 kg, respectively. AKP participants were recruited based on a self-reported visual analog scale, which indicated pain and discomfort at the knee after performing daily activities. All participants signed an informed consent document approved by the Institutional Review Board of the University of Massachusetts, Amherst.

Data Collection

Participants completed two laboratory visits; informed consent and procedural details were outlined within the first session, in addition to the performance of mock trials to confirm participants could achieve the required running speed. Biomechanical data were collected during the second visit. Participants ran along a 30 m runway at a set speed of 3.2 m.s^{-1} measured by two timing gates 6 m apart. Ten successful running trials were collected in three conditions: no brace, standard-fit brace and a custom-fit brace, Trail success was determined by completion within ± 5% of the specified speed. Fitting of the standard-fit brace consisted of a selection of standard sizes and alignment of the patellar with the brace patellar opening. The custom-fit brace was positioned and fitted in accordance to the guidelines outlined by the manufacturer using above- and below-knee measurements. Trials were completed in a blocked randomized order for which participants wore standard lab-supplied running shoes. All participants were determined to be rearfoot strikers through inspection of sagittal plane foot kinematics and vertical ground reaction forces.

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Unilateral lower-limb kinematic data were captured at 240 Hz using an 11-camera motion capture system (Oqus 3, Qualisys Inc., Gothenburg, Sweden). For asymptomatic participants, data were collected for the right leg; data for the AKP participants were collected from the symptomatic leg. Retro-reflective markers were placed at the pelvis (left and right anterior superior iliac spine, posterior superior iliac spine and iliac crests), thigh (four marker cluster placed laterally), shank (four marker cluster placed laterally), forefoot (hallux, 1st metatarsal head and 5th metatarsal base) and rearfoot (superior, lateral and medial aspects of the calcaneus). Femoral greater trochanters and lateral and medial femoral condyle and malleolus markers were additionally attached for use within a static calibration trial, which was undertaken without knee bracing. Qualisys Track Manager (QTM) (Qualisys, Inc.) software was used to synchronize kinematic data with a 1.2 x 0.6 m force plate at 1200 Hz (AMTI, Watertown, MA). The force plate was embedded in the runway and was used for identification of heel strike and toe-off events.

Data Processing and Analysis

Markers were identified and tracked using QTM, within which, temporarily occluded markers were interpolated using a polynomial spline. Three-dimensional marker coordinate date were imported to Visual 3D software (C-Motion Inc., Rockville, MD). Using static trial positional data, the lower extremity was modelled as a rigid, linked-segment system inclusive of the pelvis, thigh, shank and foot segments. The ankle and knee joint center positions were calculated as the mid-point between the medial and lateral joint markers. The hip joint center was calculated as the mid-point between the right greater trochanter marker and the pelvis-distal marker (calculated as the mid-point between the right and left greater trochanters). Marker coordinate data were filtered using low-pass bi-directional Butterworth filters at 8 Hz. A 10 N threshold was used to determine heel strike and toe-off events from vertical ground reaction force profiles. Angular data for hip, knee and ankle joints and thigh, shank and foot segments were calculated with Cardan angles with an X-y-z rotation sequence and normalized to 101 points for the stance phase (heel strike to toe-off).

Normalized angle data were input to a custom MATLAB program (Math Works Inc., Massachusetts, USA) for each trial and each participant. Using a modified vector coding technique [18], coupled joint angles (hip-knee and knee-ankle) were derived for each condition (standard-fit, custom-fit and no brace), in addition to segment angle couplings (thigh-shank and shank-foot) which were computed relative to a fixed laboratory orthogonal coordination system (Table 1). Ranging from 0° to 360°, coupling angle outcomes have been previously interpreted through division into eight categories with combinations of in-/anti-phase and distal- /proximal-dominancy [19]. Divided by group and condition, frequency analyses were conducted for each coupling across stance, representing the duration of the coupling angle in each of the eight categories. Using a circular statistics approach, coordination variability was calculated for each coupling as outlined by Chang et al. [18].

Coupling	Coupling Planes	Abbreviation	Supporting Literature
Hip-knee	Sagittal-sagittal	$H_{Flex/Ext}$-$K_{Flex/Ext}$	[13,17]
	Frontal-frontal	$H_{Add/Abd}$-$K_{Add/Abd}$	[4,20]
	Transverse-transverse	H_{Rot}-K_{Rot}	[8,9]
Knee-ankle	Sagittal-sagittal	$K_{Flex/Ext}$-$A_{Dorsi/Plantar}$	[21]
	Transverse-frontal	K_{Rot}-$A_{Inv/Eve}$	[21]
Thigh-shank	Transverse-transverse	T_{Rot}-S_{Rot}	[22]
Shank-foot	Transverse-frontal	S_{Rot}-$F_{Inv/Eve}$	[12]

Table 1: Joint and segment couplings with abbreviations and supporting literature.

Statistical Analysis

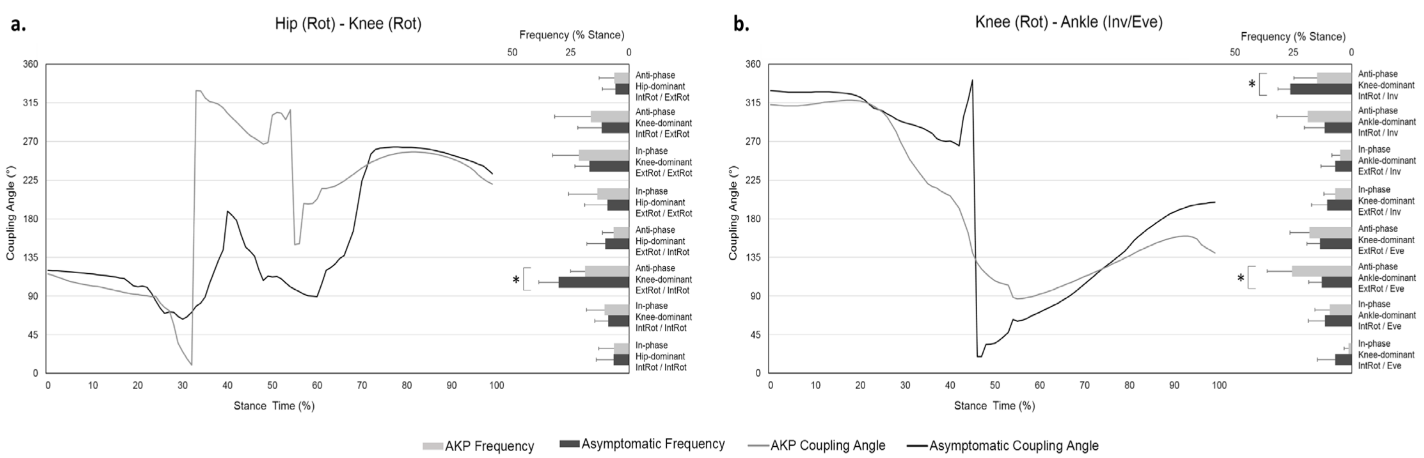
Following normality testing of coupling angle frequency data ($P < 0.05$), a Mann-Whitney U test was performed to explore the differences between AKP and asymptomatic cohorts within the no brace condition. Friedman's repeated measures ANOVA test enabled the statistical appraisal of within group, between conditions frequency statistical differences. Pairwise comparisons were performed with a Bonferroni correction for multiple comparisons. All discrete statistical analyses were conducted using SPSS software (IBM SPSS Statistics 23, SPSS Inc., Chicago, IL). Effect Sizes (ES) were calculated from z statistics outputs [23] and interpreted in accordance to Cohen's large (0.8), moderate (0.5) and small (0.2) boundaries [24].

Based on random field theory, One-Dimensional Statistical Parametric Mapping (SPM1D) enabled the statistical analysis of the continuous data outputs [25]. Following normality testing ($P < 0.05$), a non-parametric two-sample t-test was performed to appraise the between group coordination variability differences. To assess the between conditions, within group coordination variability differences across the stance phase, a non-parametric repeated measures ANOVA was additionally performed. To further investigate any significant coordination variability difference between conditions, non-parametric two-sample t-tests were conducted. An alpha criterion of 0.05 was set a priori.

Results

Influence of AKP on Coordination and Variability During Running

Hip-knee and knee-ankle couplings were found to be significantly different for AKP and asymptomatic cohorts during stance ($P < 0.05$; $ES > 0.5$; Figure 1). For H_{Rot}-K_{Rot} coupling (Figure 1a), AKP participants spent a reduced proportion of stance with anti-phase, knee-dominant coordination (hip external rotation/knee internal rotation) in comparison with asymptomatic participants (11% frequency difference; $P = 0.01$; $ES = 0.64$). Analyses of K_{Rot}-$A_{Inv/Eve}$ (Figure 1b) revealed greater anti-phase, ankle-dominance (knee external rotation/ankle eversion) for the AKP cohort ($P = 0.01$; $ES = 0.62$). AKP participants additionally spent significantly more time in anti-phase, knee-dominance (knee internal rotation/ankle inversion) than their asymptomatic counterparts (11% frequency difference; $P = 0.01$; $ES = 0.59$). No statistically significant coordination variability differences were found between the AKP and asymptomatic cohorts.



Figures 1(a,b): Inter-joint coupling angles across stance and coordination frequencies of asymptomatic and AKP cohorts with no bracing; *$P < 0.05$.

Influence of Knee Bracing on Coordination and Variability

Significant coordination differences were revealed for AKP participants for $H_{Add/Abd}$-$K_{Add/Abd}$ and T_{Rot}-S_{Rot}, and asymptomatic participants for K_{Rot}-$A_{Inv/Eve}$, T_{Rot}-S_{Rot} and S_{Rot}-$F_{Inv/Eve}$ couplings ($P < 0.05$; Fig. 2). Participants spent a significantly greater time with in-phase hip-dominance (hip adduction/knee adduction) coupling when wearing a standard-fit brace, in comparison with a custom-fit brace (2% difference; $P = 0.04$; $ES = 0.39$; Figure 2a). Although T_{Rot}-S_{Rot} differences were identified for the AKP cohort between the three bracing conditions, no paired differences were found ($P > 0.05$; Figure 2b). K_{Rot}-$A_{Inv/Eve}$ coupling analyses revealed that when wearing no brace, asymptomatic participants spent significantly more time with in-phase ankle-dominance (knee external rotation/ankle inversion) in comparison with the standard-fit brace (2% difference; $P = 0.04$; $ES = 0.39$; Figure 2c). The asymptomatic

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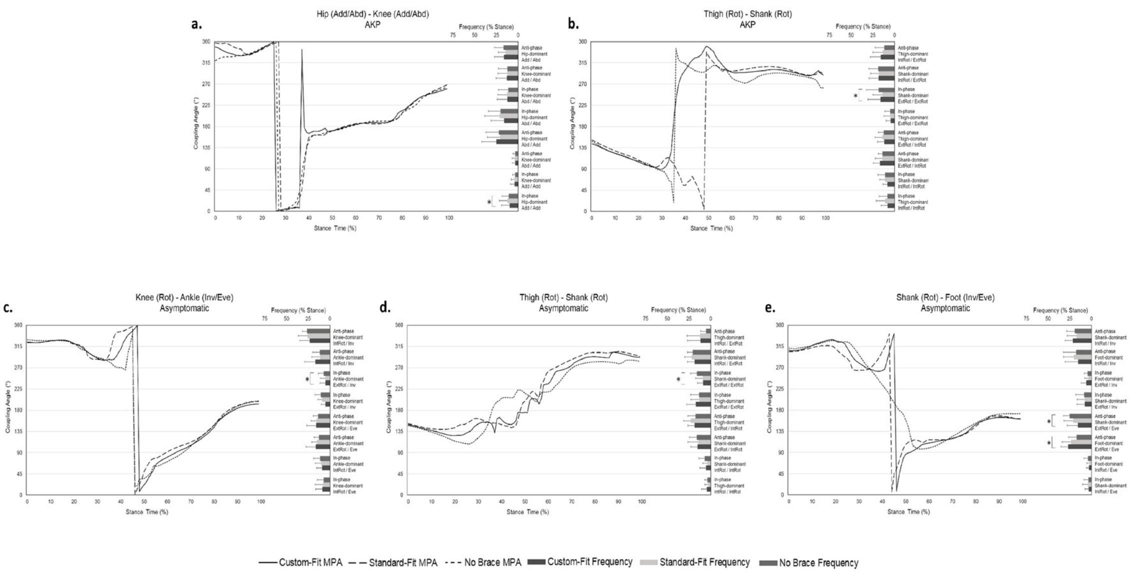
cohort additionally spent a significantly greater proportion of stance with in-phase, shank-dominant coordination (thigh external rotation/shank external rotation) when wearing no brace (16 ± 8%) in comparison with the standard-fit brace (9 ± 8%; P = 0.01; ES = 0.44; Figure 2d) and the custom-fit brace (9 ± 6%; P = 0.04; ES = 0.39). For S_{Rot}-$F_{Inv/Eve}$, custom-fit bracing significantly increased the duration asymptomatic participants spent in anti-phase foot-dominant (shank external rotation/foot eversion) in comparison with the standard-fit (P = 0.04; ES = 0.39) and no brace conditions (P = 0.00; ES= 0.50; Figure 2e). The asymptomatic cohort spent longer in anti-phase shank-dominance (shank external rotation/foot eversion) when in the no brace condition (P = 0.00; ES = 0.56) in comparison with the standard-fit and custom-fit brace conditions.



Figures 2(a-e): Inter-joint/inter-segment coupling angles and coordination frequencies of standard-fit, custom-fit and no brace conditions within asymptomatic and AKP groups; *P < 0.05.

Significant coordination variability differences were found for AKP K_{Rot}-$A_{Inv/Eve}$ (P < 0.05; Figure 3). At 10% of stance, AKP group K_{Rot}-$A_{Inv/Eve}$ variability was greatest for the no brace condition (8.9˚), in comparison with the standard-fit (6.0˚) and custom-fit (7.3˚) conditions. Further exploration revealed no paired significant differences between K_{Rot}-$A_{Inv/Eve}$ conditions.

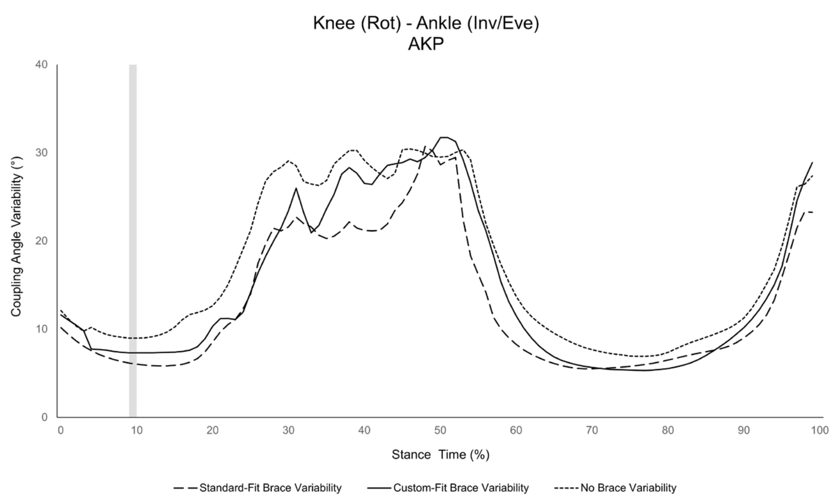


Figure 3: Coupling angle variability for AKP group K_{Rot}-$A_{Inv/Eve}$ across the stance phase for standard-fit, custom-fit and no brace conditions; the shaded region indicates statistical significance from SPM1d analyses (P < 0.05).

Discussion

The purpose of the current study was to investigate lower-extremity kinematic couplings for AKP participants during running without bracing and when wearing standard- and custom-fit knee braces. It was firstly hypothesized that AKP participants' coordination and coordination variability would differ from their asymptomatic counterparts. The AKP cohort had different H_{Rot}-K_{Rot} and K_{Rot}-$A_{Inv/Eve}$ coordination patterns across stance; however, no group differences were identified for coordination variability. The first hypothesis was subsequently supported in part. It was additionally hypothesized that coordination and coordination variability would differ between standard-fit, custom-fit and no brace conditions for the AKP cohort, but the braced conditions would have no influence on asymptomatic couplings. The secondary hypothesis was supported by AKP $H_{Add/Abd}$-$K_{Add/Abd}$ and T_{Rot}-S_{Rot} coordination and K_{Rot}-$A_{Inv/Eve}$ coordination variability differences across brace conditions. As coordination differences were additionally identified in the asymptomatic group, the secondary hypothesis was also partially supported.

Influence of AKP on Coordination and Variability During Running

The AKP cohort used different H_{Rot}-K_{Rot} and K_{Rot}-$A_{Inv/Eve}$ strategies than the asymptomatic cohort to complete the running task, spending significantly less time in knee-dominant movement patterns during stance (Figure 1). The weight acceptance and loading phases (early-and mid-stance) were achieved with a greater dominance of knee angular motion (internal rotation) for the asymptomatic cohort when coupled with hip external rotation and ankle inversion. The findings are consistent with Wilson and Davis [9], who reported greater knee external rotation across many activities, including running, for subjects with PFPS. During mid- and late-stance, AKP participants typically employed knee external rotation couplings, whereas the asymptomatic cohort transitioned through knee internal rotation to external rotation at toe-off. External knee rotation has been found to contribute to heightened patellofemoral joint contact pressure [26] and therefore appears a likely mechanism of AKP. However, further study is required to determine whether the AKP coupling strategy is causative or a mechanism for pain avoidance.

With reduced time spent in knee-dominant couplings, the AKP cohort spent significantly longer than their asymptomatic counterparts in anti-phase ankle-dominant couplings for K_{Rot}-$A_{Inv/Eve}$ (external rotation/eversion). The current study findings were supportive of previous associations between PFPS runners and asynchrony (anti-phase motion) in coupling outcomes [27], however, significantly greater anti-phase couplings were also found for asymptomatic participants. Therefore, the pathomechanic nature of anti-phase motion as suggested by Dierks, et al. [27] was not supported by the current research findings. In addition to the potentially heightened importance of joint dominancy over motion type (in-/anti-phase) for AKP development, the findings of significance for inter-joint rather than inter-segment coupling are indicative of the important contribution of multiple segments to the altered change in control of movement with pain.

The appraisal of coordination variability between asymptomatic and AKP cohorts revealed no significant differences for the selected couplings across the stance phase. It is possible that the pain levels of the AKP participants may not have been sufficient to identify coordination variability differences at the set level of significance, as was anticipated in accordance with the dynamical systems theory [14].

Influence of Knee Bracing on Coordination and Variability

Knee bracing aims to provide external support to impaired internal structures. As such, the role of the knee brace in effectively assisting AKP moderation was anticipated to be evidenced through altered coupling mechanics within the AKP cohort, with knee bracing having little influence on the asymptomatic cohort couplings. Pain was found to be a modifying factor in how individuals respond to knee bracing during running, with standard- and custom-fit braces having a greater influence on couplings for the asymptomatic cohort in comparison with the AKP participants. The AKP cohort used significantly different $H_{Add/Abd}$-$K_{Add/Abd}$ and T_{Rot}-S_{Rot} couplings between conditions, although no paired differences were identified for T_{Rot}-S_{Rot}. For the knee orthoses to be fully effective, differences between braced and no brace conditions were expected for the AKP cohort. Post-hoc testing revealed $H_{Add/Abd}$-$K_{Add/Abd}$ differences to exist between the standard- and custom-fit braces, with no difference between the braced and no brace conditions. Subsequently, coordination and coordination variability analyses of standard- and custom-fit knee bracing provided little support for the ability of current knee braces to effectively contribute to transitioning AKP participants to healthy coordinative motion patterns. In addition to pain typically increasing, lower-limb kinematics may be altered with increased running time [27]; it is possible that knee bracing functionality may become more prominent during the study of prolonged running.

Asymptomatic individuals were found to run with altered coupling mechanics within the braced condition in comparison with the no brace condition for K_{Rot}-$A_{Inv/Eve}$, T_{Rot}-S_{Rot} and S_{Rot}-$F_{Inv/Eve}$. As highlighted by Bellemans [28], even subtle changes to the well-designed patellofemoral mechanism are anticipated to have important biomechanical implications, subsequently, the findings are suggestive of the potentially detrimental mechanical impact of wearing either the standard- or custom-fit brace as a preventative measure. No paired statistical coordination variability differences were found for couplings within either the asymptomatic or AKP groups. As no coordination variability differences were found between the groups in the no brace condition, the finding of no paired within-group bracing differences is favorable for the use of standard- and custom-fit knee braces. Although the braces aim to provide external support to the knee joint, inter-joint and inter-segment coordination variability was found not to be compromised

Conclusion

When running with AKP, participants have been shown to alter their hip-knee and knee-ankle kinematic couplings compared to asymptomatic cohorts. The use of knee bracing alone may not be sufficient to influence coordination patterns in attempt to transition AKP lower-limb movement patterns to that of asymptomatic individuals. The results suggest the mechanisms for knee pain extend beyond the knee joint and therefore, consideration of proximal and distal lower-limb segments may be most effective for injury prevention strategies.

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