INTRA-LIMB JOINT COUPLING PATTERNS DURING THE USE OF THREE LOWER EXTREMITY EXERCISE MACHINES

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The purpose of this study was to preliminarily describe sagittal plane joint coupling patterns for a spectrum of common lower extremity exercises. Each participant performed 3, 10 second sessions on a stationary bicycle, elliptical and treadmill. Intra-limb coupling angles of the hip and knee for two recreational athletes were quantified using vector coding techniques on randomly selected cycles from each movement. Variability patterns within the same movements were repeatable within and between each participant while each movement's distinguishable variability pattern differed both spatially and temporally between pieces of exercise equipment. These findings suggest that each exercise machine studied is distinguishable characteristics in its variability pattern. Comparison of variability patterns might be a useful method in the design of functional training exercises to aid in optimally mimicking task kinematics.

KEY WORDS: biomechanics, dynamical systems, variability, vector coding, specificity.

INTRODUCTION: Running is a desirable skill utilized in sports, exercise and everyday life to maintain an active, healthy lifestyle. Unfortunately, running can be demanding on the body and has been shown to be attributed to many lower extremity injuries (Sutton, 1984) or be difficult to perform if an injury is present (Dauty, Potiron-Josse & Rochcongar 2003). Multitudes of training and rehabilitation protocols involve mimicking the running movement as closely as possible by performing lower extremity cyclic motions to train neuromuscular coordinative structures associated with this skill (Kilding, Scott & Mullineaux, 2007). A fundamental requirement to correctly simulate the running motion during a training protocol involves reproducing the lower extremity joint kinematics seen during running. Inability to adhere to this specificity principle can result in deficient motor learning patterns that can lead to possible future injuries or inefficient muscle recruitment patterns (Kilding et al., 2007).

Commonly used exercise devices that constrain the distal lower extremity to adhere to movements range from simple circular movements produced by a fixed length pedal crank in bicycles to a more sophisticated cyclical motion produced by a cam commonly referred to as an "elliptical" motion. Running is an open chain movement where the distal limb is not constrained, which introduces variances in movement that are beneficial for locomotion (Heiderscheit, 2000) but are difficult to reproduce for training. If the training standard is to mimic the lower extremity actions seen during running, it is necessary to establish kinematic patterns associated with currently used training interventions to gauge differences in seemingly similar motions. The ability to quantify differences in movements may help optimize development of functional training exercise movements or aid in the design of equipment to accurately facilitate movement patterns. It is therefore the aim of this study to compare the joint coupling patterns of both a simple cyclical movement (bicycle) and a supposedly more complex movement (elliptical) to the standard of running.

METHOD: Data Collection: Two recreational athlete, males participated in this study (1: age=28 yrs, height=192 cm, mass=94 kg, leg length=103 cm; 2: age=26 yrs, height=175 cm, mass=81 kg, leg length=79 cm). Individual retro-reflective markers were placed on the sacrum, bilateral ASIS, medial/lateral femoral epicondyles & malleoli with rigid clusters attached to the thigh and shank to describe rotations of the right hip and knee joint in the sagittal plane. Participants were asked to stand in an anatomically neutral stance while an anatomic static calibration was captured. Participants then performed 3, 10 second sessions of activity on a generic commercial treadmill (CS6.0; TRUE Fitness, St. Louis, MO, USA), elliptical machine (Prp350XL; Octane Fitness, Brooklyn Park, MN, USA) and stationary bicycle (Schwinn Evolution-SR; Nautilus, Vancouver, WA, USA). Speed was only controlled during the treadmill sessions which were performed at 3.8 m/s. Marker locations were captured using four digital motion cameras (Eagle-4; Motion Analysis Corp., Santa Rosa, CA) at a sampling frequency of 60 Hz with Cortex V1.0 software (Analysis Corp., Santa Rosa, CA, USA).

Data Analysis: Data were exported to Visual 3D (3.9, C-Motion, Germantown, MD, USA) for initial analysis. Data were filtered using a fourth-order Butterworth low-pass filter with a cutoff frequency of 6-Hz as determined by residual analysis (Winter, 1990). Joint angles were calculated for both the hip and knee for all trials with the hip being 0° and the knee 180° during standing posture with extension values being negative. Calculated parameters were further analyzed in Matlab R2007b (Mathworks, Natick, MA) where gait cycles were determined using thigh velocity. The start of each movement cycle for the elliptical and treadmill was defined as the maximum thigh position in the anterior direction relative to the body, while the start of the bike cycle was determined to begin at the thigh's most superior point. Data from each determined cycle were time normalized to 101 points representing 100% of the respective gait cycle. Three nonconsecutive trials for each condition were chosen randomly to represent each movement condition. Angle-angle diagrams were constructed to qualitatively describe the range and timing of joint movements. Vector coding techniques were then implemented in Excel (Microsoft Corp., Redmond, WA) to quantify intra-segmental coupling characteristics between all three movement conditions. (Heiderscheit, Hamill, & Emmerik, 2002)

RESULTS:

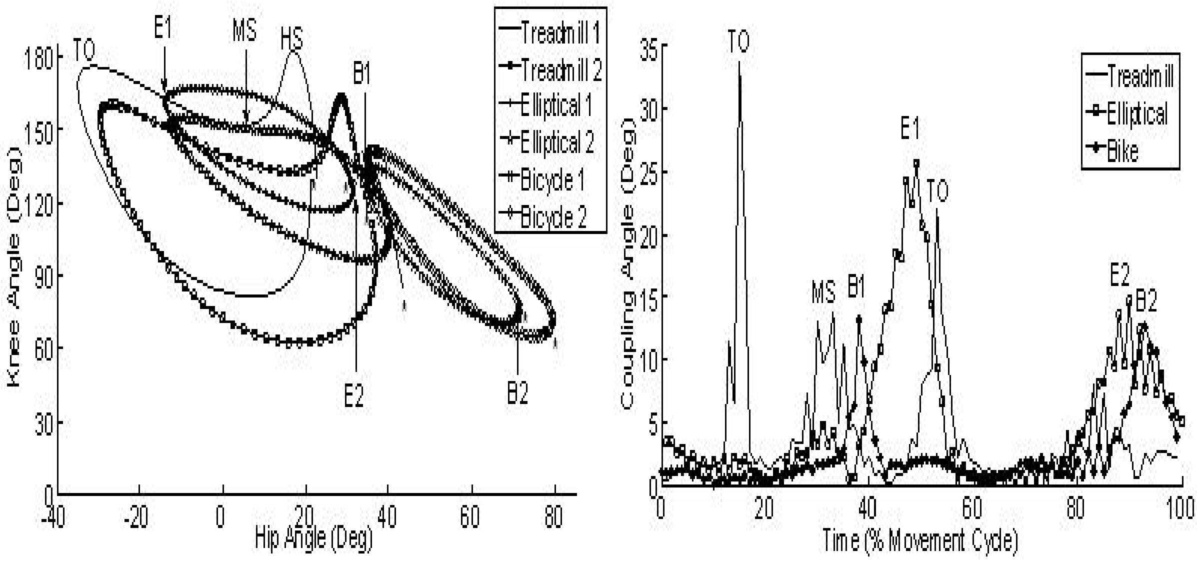

Figure 1a (left): Relative motion plots of the Hip and Knee joints during three different cyclical movements for two participants. Movement is counter-clockwise about each curve beginning at the asterisk (*). Heel-strike (HS), Mid-Stance (MS) & Toe-Off (TO) are visually distinguishable points during stance phase of the treadmill movement; E1 & E2 on the elliptical, B1 & B2 during the bike movement are abrupt changes in joint angle. Hip angle= 0° & knee angle =180° at standing posture.
Figure 1b (right): Flexion/Extension coupling angle variation plots between the Hip and Knee for the 1st participant obtained using vector coding. HS, MS, TO, E1, E2, B1 & B2 correspond to the same points labelled in Figure 1(left) and points of local maximums in variation.

After initial visual observation of constructed relative motion plots, it was determined by visual inspection that the within-participant variance between trials for each movement was considered negligible in the demonstration of the joint coupling patterns for each respective movement. Therefore, the ensemble average of the three trials chosen for each individual are considered to be adequate representations of the angular joint motions demonstrated during this study. These average relative motion plots are shown in Figure 1a. Movements are superimposed on the same figure to qualitatively compare inter-movement and intra-participant variation. The key gait determinants during stance phase (Heel-strike (HS), Mid-stance (MS) & Toe-off (TO)) are labelled on the treadmill plot for reference. Elliptical and bicycle movements were hypothesized to be more generic cyclical movements but did have key transition points in movement similar to that in running gait which are labelled; E1 & E2 for the elliptical and B1 & B2 for the bicycle.

A more quantitative tool for gauging differences in angular motions between movements at given points during each cycle can be seen in Figure 1b. Again, the same points are labelled in this figure as in Figure 1a for easy comparison. It should be noted that intra-movement variability was strikingly similar between participants (less than 3° SD & 1% SD) for all points in the gait cycle and therefore only one participant's coupling angle pattern is shown.

Treadmill running appeared to be the most complex movement with three distinct points highlighted in Figure 1b (HS, MS & TO). A fourth recognizable point associated during late swing phase is discernable at 84% of the gait cycle, however its magnitude in variability is comparatively less than expected (8°) given the large amount of joint movement associated at this point in the gait cycle and when compared to HS (36°), MS (15°) & TO (22°). Elliptical movement did experience similar magnitudes in variability as treadmill running most apparent at E1 (23°) which also was only separated temporally from TO by 5% of their movement cycles. Despite the similarity at these points, a large magnitude was seen at E2 (21°) but did not directly correspond temporally to a point on the treadmill gait cycle. The bicycle also had two discernable points (B1 & B2) which neither corresponded in magnitude nor timing to the treadmill. B2 (9°) did however seem to occur at similar time points as E2 but was somewhat less in magnitude. All other points not labelled were similar in magnitude (less than 5°) and did not seem to experience a noticeable amount of variation.

Timing was drastically different of labelled local variation peaks when compared to running. This could be a result of separating gait cycles using thigh velocity but most likely is evidence that the movements are substantially different. It appears as if E1 and E2 might be out of phase with Heel-Strike and Toe-Off by approximately 180°. However, the rate constant for the elliptical is substantially lower indicated by the width of the variation about E1 and E2. Magnitudes were comparable between these conditions which might correspond to the more similar ranges of motion the elliptical condition had with running than compared to the bicycle which had extremely lower magnitudes in variation.

DISCUSSION: Joint kinematic ranges and associated patterns observed in our study agreed with previous research that has established typical joint movement characteristics for the three presently studied movements (Horvais, Samozino, Textoris, Hautier, & Hintzy, 2008; Raasch & Zajac, 1999; Swanson & Caldwell, 2000). Key running gait determinants labelled and used for comparison were recognizable but associations to other movement's discernable points (E1, E2, B1 & B2) need to be compared with caution considering each movement's cycle was normalized using the same methods despite the movements clearly being different. Key points for both the elliptical and bicycle condition appear to have clear transition points but both the temporal and spatial characteristics of their variability would be subjective to change depending on the exact cam or pedal profile utilized by the piece of equipment. This is comparable to the differences observed in the relative motion plots between participants on the treadmill. Participant 1 had a substantially larger leg length than participant 2 (24 cm). This could infer that at the same speed participant 1 needed a relatively smaller joint angle range to maintain speed (Dillman, 1975). This is shown in the large shift of the angle-angle plot downward and to the right in the sagittal plane angle-angle state space indicating differences in leg length would inherently dictate a separate movement pattern for each individual. However; inter-participant variability was small and consistent in both magnitude and timing within each movement category. This indicates that despite the anthropometric heterogeneity of these participants, if replication of joint coupling patterns is the ultimate goal for intervention design, assumptions that the running pattern "standard" will not deviate to a large degree may be founded. This is consistent with previous literature that has shown repeatable variation patterns at specific gait points during stance phase (Heiderscheit, Hamill, & Emmerik, 2002). This observation also gives some evidence to support hypotheses that categorically different cyclical lower extremity movements each have their own distinguishable pattern with relatively small inherent variation between individuals. A future direction of research based on these preliminary observations might involve experiments which change movement parameters of exercise interventions such as cam radius or inclination angle which might temporally shift or alter the magnitude of variation in points similar to E1, E2, B1 and B2. Observing changes in variability by altering constraints to the kinematic environment suggests that subtly different categories of movement might appear similar but actually are measurably unique. Likewise, minimal inter-movement variation of variability patterns would indicate that ability to replicate a particular movement is measurable to an extent.

CONCLUSION: This preliminary study suggests that there are unique variability characteristics distinguishing each of these commonly used lower extremity exercise movements and that these patterns also allow for small variations between individuals. Measuring changes in both the magnitude and temporal phase of joint coupling variability patterns might be beneficial in the design and evaluation of optimal movement patterns for training. Reducing specific aspects of variability between a standard movement of running and functional training movements designed by coaches, trainers or equipment designers might provide a useful tool for specificity training.

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