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Differential effects of fatigue on movement variability

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ABSTRACT

When individuals perform purposeful actions to fatigue, there is typically a general decline in their movement performance. This study was designed to investigate the effects exercise-induced fatigue has on lower limb kinetics and kinematics during a side-step cutting task. In particular, it was of interest to determine what changes could be seen in mean amplitude and all metrics of signal variability with fatigue. The results of the study revealed that post-fatigue there was an overall decrease in absolute force production as reflected by a decline in mean amplitude and variability (SD) of the ground reaction forces (GRF_V and GRF_{ML}). A decrease in mean and SD of the knee moments were also observed post-exercise. Interestingly, this trend was not mirrored by similar changes in time-dependent properties of these signals. Instead, there was an increase in the SampEn values (reflecting a more variable, irregular signal) for GRF force profiles, knee kinematics and moments following the exercise-induced fatigue. These results illustrate that fatigue can have differential effects on movement variability, resulting in a both an increase and decrease in movement variability, depending on the variable selected. Thus, the impact of fatigue is not simply restricted to a decline in force producing capacity of the system but more importantly it demonstrates that the ability of the person to perform a smooth and controlled action is limited due to fatigue.

1. Introduction

Fatigue can have a widespread impact on biological functioning, altering the capacity of most systems to operate at the desired level [1,2]. The inevitable consequences of fatigue, which can alter neuromuscular processes both centrally and peripherally, is a decrement in aspects of movement performance for a given individual. Some examples of the specific neuromuscular changes seen with fatigue include alteration of the pattern of muscle activity, increases in isometric force fluctuations, postural tremor and altered dynamics of limb motion [1–3]. One common indices of the impact of fatigue is the general decrease in the absolute amount (amplitude) of force produced although increasing emphasis has also been directed toward changes in the pattern of variability for the respective motor output. More specifically, it has been reported that, in conjunction with an observed decline in the force amplitude, fatigue can also be characterized by systematic changes in motor variability [4,5].

The tendency to include assessments of variability has emerged since all movements exhibit a degree of variability – indeed, it is an intrinsic characteristic of action, and, consequently, has been classified as a normal and functional property of the neuromotor system [6,7]. A key focus has been to assess what factors alter the typical pattern of variability and what the resultant changes reveal about the workings of the neuromuscular system. While variability is a common outcome during movement [5], there are various ways in which it can be assessed. A typical approach is to determine the level of deviation in the amplitude of a signal, using measures such as standard deviation, standard error and/or coefficient of variation, as metrics for the level of variability. However, these metrics are somewhat restrictive in that they only capture variability in one direction, thus they may overlook alterations in a given signal over time. Lipsitz and Goldberger [8], demonstrated a decrease in the pattern of heart rate variability over time was better able to identify persons at risk as compared to changes in measure of amplitude variability. Consequently, in addition to amplitude-dependent assessments of variability, a variety of measures have been developed to capture the pattern of signal deviation over the course of the task [8–11].

Recent studies have since advocated the importance of using both amplitude- and time-dependent assessments of physiological variability and complexity. The reported findings have shown that alterations in the time and/or amplitude of signal variability can

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provide insight as to the impact aging has on motor processes [12], can be used to distinguish between patients with differing neurological disorders [11], and be used to assess individuals at the risk of injury and damage [13–15]. With specific regard to the link between variability and injury, several studies have reported that individuals who exhibit lower levels of complexity and variability of lower limb mechanics during whole body dynamic actions are often at increased risk of injuring the anterior cruciate ligament (ACL) [13,16]. Given that damage to the ACL is one of the most common debilitating knee injuries in the athletic population [17,18], there is evidence to support the view that loss of variability may be a precursor for increased likelihood of injury and damage.

While there is a growing body of evidence to support this view, much of the focus has now switched to assess those factors that may directly produce changes in variability and complexity. Fatigue is one factor that has been proposed to cause a progressive loss of variability which has a negative impact on overall physiological processes leading to a decline in function and the increased possibility of injury [8,11]. Thus there is a general view that the relatively transient effects of fatigue on movement variability can have long-term consequences for risk of injury. The study was designed to assess the impact exercise-induced fatigue had on lower limb kinetics and kinematics during a dynamic action (i.e., a side step cutting task). In particular, it was of interest to assess what impact fatigue had on amplitude- and time-dependents feature of movement variability. Based upon previous studies, it was predicted that this intervention would result in an overall decrease in all metrics of signal variability.

2. Methods

Eleven young subjects (20 ± 0.9 years; 1.67 ± 0.1 m; 63.2 ± 10.1 kg) participated in this study. All participants were physically active and reported no known neurological/cognitive disorders, or history of neuromuscular injury that could influence performance. In addition, clearance from the team physician to practice and play in games was required at the time of data collection. The dominant leg (defined as the leg that the participant would use to kick a soccer ball as far as possible) was analyzed. All participants provided written informed consent approved by University Institutional Review Board.

3. Protocol

The specific movement task all participants were asked to perform was a side-step cutting action. This task consisted of a running approach, placement of the dominant foot on the force plate followed by a 45° cutting maneuver to the contralateral side of the foot [19]. This dynamic action was performed both prior to- and after-fatigue.

Prior to performing the cutting task, participants were permitted a 10-min warm-up period, which consisted of self-directed cycling and stretching. After this warm-up, 40 reflective markers were placed on specific anatomical landmarks about the hip and lower limbs. The same researcher placed the markers on all subjects. Marker placement reliability for measurement error has been reported previously with good to excellent reliability [20]. Thirty markers were tracking markers consisting of 1 on each postero-superior iliac crest and anterior iliac crest, a four marker cluster on each thigh and shank, and a five marker cluster on each foot. The remaining 10 were calibration markers placed on the greater trochanters, medial/lateral femoral condyles, and medial/lateral malleoli. The same researcher placed the markers on all participants. Standing and dynamic calibration trials were done to calculate hip joint center. After those trials, the calibration markers were removed.

When performing the side-step cutting task, a visualization of two soccer scenarios were randomly generated and projected onto a screen in front of the participant [20]. The two scenarios consisted of an image of either a ball cutting to one side or the ball stopping. The un-anticipation factor and the environment were intended to mimic a decision-making soccer movement task. Prior to data collection, the participants practiced a minimum of three trials or until they felt comfortable with the tasks. The participants performed five trials for each task pre- and post-fatigue. There was a 1-min rest period between pre-fatigue trials to minimize tiredness. Consequently to the fatigue protocol, the same procedure was conducted with no rest between trials to maintain fatigue levels.

3.1. Fatigue protocol

To determine the parameters for the fatigue protocol, participants started by performing a VO2peak test. The protocol required participants to run at 9 km/h for 5 min followed by l-km/h speed increments every 2 min until exhaustion [21]. Following the VO2peak test, each participant rested for 5-min prior to starting the fatigue protocol. Immediately after this rest period, participants alternated between 2 running speeds throughout 30-min treadmill run. Six intervals consisting of running at a speed of 70% of the final VO2peak speed for 4 min followed by running at a speed of 90% of their final VO2peak speed for 1 min were conducted. The estimated time for the VO2peak test was 15 min, which, when combined with the 30-min treadmill fatigue protocol, equalled 45 min and simulated 1 half of a collegiate soccer match [21].

4. Equipment

Kinematic measures of the lower extremity were captured using an eight-camera high-speed motion capture system (VICON, Oxford, England) with a sampling rate of 270 Hz. Ground reaction force data were obtained through two force plates (Bertec, Columbus OH, USA) sampling at 1080 Hz. From the standing trial a kinematic model (pelvis, thigh, shank, and foot) was created for each participant using Visual 3D software (C-Motion, Germantown MD, USA) with a least-squares optimization. This kinematic model was used to quantify the motion at the hip, knee, and ankle joints. Marker trajectories and ground reaction forces were filtered with a 4th order low-pass Butterworth filter with a cut off frequency of 7 Hz and 25 Hz, respectively.

A metabolic cart (model Vmax 29c;CareFusion, San Diego, CA) was used prior to the fatigue protocol to measure submaximal oxygen consumption and peak oxygen consumption (VO2peak) [21]. The flow sensor was calibrated against a 3.0-L syringe, and carbon dioxide and oxygen sensors were calibrated against known gases before the VO2peak test. The flow sensor and mouthpiece were attached to a headset, which was used to collect expired air. An average of the 3 highest, continuous, 20-s interval oxygen consumption measurements was used to calculate VO2peak. A heart rate monitor (model FS2C; Polar Electro, Lake Success, NY) was used to collect measurements of resting and exercise heart rates during the entire test.

5. Data analysis

5.1. Amplitude-dependent measures

Standard descriptive measures were used to assess changes in variability (SD) and average (mean) of the kinematic and kinetic signals.