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N. Cortes

J. Onate

S. Morrison
Old Dominion University

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Differential Effects of Fatigue on Movement Variability

N. Cortes[1], **J. Onate**[2], and **S. Morrison**[3]

[1]Sports Medicine Assessment, Research & Testing (SMART) Laboratory, George Mason University, USA

[2]School of Health and Rehabilitation Sciences, The Ohio State University, USA

[3]School of Physical Therapy and Athletic Training, Old Dominion University, USA

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.

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 towards changes in the pattern of variability for the respective motor output. More

Corresponding Author: Nelson Cortes, Address: Sports Medicine Assessment, Research & Testing (SMART) Laboratory, George Mason University, 10900 University Blvd, Bull Run Hall 208B, Manassas, VA 20110, Phone: 703-993-9257, FAX: 703-993-2025, ncortes@gmu.edu.

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 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.

Methods

Eleven young subjects (20±0.9years;1.67±0.1m;63.2±10.1kg) 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 analysed. All participants provided written informed consent approved by University Institutional Review Board.

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-minute 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.

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

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 4^{th} order low-pass Butterworth filter with a cut off frequency of 7Hz and 25Hz, 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.

Data Analysis

Amplitude-dependent Measures

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

Time-dependent Measures

The degree of regularity of the kinematic and kinetic signals was assessed using Sample Entropy (SampEn) analysis. This analysis determines the conditional probability of the signal by providing a measure of the (logarithmic) likelihood that runs of patterns that are close for m observations (epochs) remain close for incremental ($m+1$) comparisons [9,10]. This analysis returns a single value for a given time series within the range of 0–2. Higher SampEn values represent lower repeatability of vectors of length m to $m+1$, marking lower predictability of future data points, and greater irregularity within the time-series. Lower values represent a greater repeatability and are thus a marker of higher regularity (more complexity) in the time series.

Statistical Analyses

A within-subject, repeated measures mixed generalized linear model (GLM) was used to assess for differences for the various kinematic and kinetic data before- and after-fatigue. Where significant effects were reported, post hoc evaluations were performed using Tukey's Honestly Significant Difference (HSD) test. Effect sizes based on the pre-post differences for each measure were expressed as Cohen's *d* [22]. All statistical analyses were performed using SAS statistical software (SAS Institute Inc., NC), with the risk of Type I error set at $p<0.05$.

Results

Mean Amplitude-dependent differences

Examples of the typical ground reaction force (GRF) curves observed during a series of trials for a single subject is shown in figure one. The curves shown reflect the forces in the vertical and anterior-posterior (AP) directions. This figure highlights the effects of the fatigue protocol on both the magnitude and pattern of ground reaction forces. Analysis of the average amplitude revealed significant differences for the AP ($F_{1,10}=5.16$; $p<0.05$), medio-lateral ($F_{1,10}=6.92$; $p<0.05$), and vertical ($F_{1,10}=12.19$; $p<0.05$) ground reaction forces. For these measures, the differences due to fatigue were of small magnitude based on effect sizes for the AP ($d=0.11$), medio-lateral ($d=-0.03$) and vertical forces ($d=0.09$). Significant differences were also observed for ankle dorsiflexion angle ($F_{1,10}=5.68$; $p<0.05$, $d=-0.09$), hip abduction angle ($F_{1,10}$=20.68; p<0.05, d=−0.43), hip abduction moment ($F_{1,10}$=5.87; p<0.05, d=0.14) and knee abduction angle ($F_{1,10}$=12.67; p<0.05, d=0.22). For all measures, the average amplitude decreased significantly following the fatigue intervention.

Amplitude-dependent Changes in Variability

The results revealed a significant fatigue effect for the level of variability (SD) of the forces in the AP ($F_{1,10}$=8.39; p<0.05, d=0.33), medio-lateral ($F_{1,10}$=7.11; p<0.05, d=0.29) and vertical ($F_{1,10}$=5.95; p<0.05, d=0.24) directions. Post hoc analysis revealed that the level of variability decreased for these force measures following the intervention. A significant fatigue effect was also observed for the variability (SD) of the knee flexion ($F_{1,10}$=5.54; p<0.05, d=−0.18), and abduction moments ($F_{1,10}$=6.65; p<0.05, d=0.33). The degree of variability across the knee moments decreased significantly following the fatigue protocol. The overall changes in the mean and SD of the GRF values (vertical and anterior-posterior) as a function of fatigue are shown in Figure 2.

Time-dependent Changes in Variability

A significant fatigue effect was observed for the SampEn values for the vertical ($F_{1,10}$=5.77; p<0.05) and medio-lateral ($F_{1,10}$=8.53; p<0.05) forces. Post hoc analysis showed that the SampEn values for these force measures increased following the fatigue protocol, indicating greater irregularity (variability) in the force signal over time. The differences due to the intervention were of moderate magnitude based on effect sizes for vertical (d=−0.52) and medio-lateral forces (d=−0.41). A significant fatigue effect was also observed for the knee abduction angle ($F_{1,10}$=15.22; p<0.05, d =−0.60) and the moment about the knee during abduction ($F_{1,10}$=5.03; p<0.05, d = −0.39). As with the force measures, the SampEn values for these variables all increased significantly following the fatigue protocol. Changes in the average SampEn values for the vertical and anterior-posterior GRF measures and the knee abduction moment are shown in Figure 3.

Discussion

This study was designed to assess the impact fatigue has on lower limb kinetics and kinematics signal amplitude, variability, and regularity during a side-step cutting task. Consistent with previous research we hypothesized that fatigue would result in an overall decrease in mean amplitude and all metrics of signal variability. Our results partially support our hypothesis. While an overall decrease in mean amplitude and variability (SD) of the ground reaction forces (GRF_V and GRF_{ML}) and knee moments were seen following fatigue, this pattern was not observed for the time-dependent properties of these same signals. Instead, there was an increase in the variability (more irregular over time) for GRF force profiles, knee kinematics and moments following exercise-induced fatigue. These results illustrate that fatigue can have a differential effect on motor variability, resulting in both an increase and decrease in movement variability, depending on the variable selected. Thus, the impact of exercise-induced fatigue is not simply restricted to a decline in force producing capacity of the system, but more importantly influences the ability of the person to perform a smooth and controlled movement pattern.

Impact of Fatigue on Lower Limb Dynamics

The effects of fatigue can have a wide range of effects on human physiological systems, with the resulting impact typically being reflected by an overall decline in ability in performance. The results of this study showed that, when performing a rapid side-step action, exercise-induced fatigue significantly affected knee kinematics and ground reactions forces. Specifically, there was a reduction in the AP, ML and vertical GRFs coupled with a concurrent decrease in knee flexion angle and the moments. Interestingly, changes were not simply restricted to a decline in the specific amplitude measures, as significant increases in the structure or pattern of variability over time for these same force and knee joint motion measures were also observed. Consequently, the effects of fatigue was manifested by reciprocal pattern of changes in the selected measures of variability, with increases being seen in signal regularity and decreases being found for signal amplitude. While signal variability or complexity changes have been broadly viewed from a uni-directional perspective[8,11,13], there is some evidence to support the view that increase and/or decreases in the various indices of variability can be observed depending on the task and variable being assessed[23,24].

A pertinent issue concerns the link between changes in the pattern of variability and movement performance. One of the general features of performing a task to fatigue, is the tendency for the absolute force producing capacity (i.e., reduced mean) to decline over time[25–27]. What is also often observed during static isometric tasks that require the maintenance of a specific force output is an increase in the level of variability concurrent with the decline in force production[4,25,28]. It is important to note that the latter findings tend to be observed under tightly controlled task conditions, typically only involving a small number of muscles about a single joint with force production being reduced to one plane. Consequently, there has been a degree of task-dependence specificity to the findings reported. Therefore, the finding of the current study builds upon and extends from previous studies by illustrating that a differential pattern of change in movement variability can be observed during whole body, multi- joint movements, and it also decreases post-fatigue as in other research.

Loss of Coordination with Fatigue

While the decline in vertical ground force (mean and SD) probably reflects an overall decline in the absolute force producing capacity of the specific muscles following fatigue[2,26,27], the concurrent decrease in the pattern of regularity or signal smoothness over time may represent a different outcome. Previous research has reported that an increase in signal complexity from some optimal level of can often be reflective of a decline in movement coordination and/or control[9,13]. Consequently, the observed increase in complexity of the GRF and knee joint kinematics following the exercise intervention may illustrate that one outcome of fatigue was a general decline/loss of coordination during the movement.

Interestingly, the specific variables significantly affected by the fatiguing exercise were restricted to the GRF's and knee joint range of motion and moments. Given that changes in angle and/or loading about the knee joint are widely considered as precursors for ACL damage[29,30], the finding highlighting that these specific measures were affected by fatigue is a potential cause for concern. If this general loss of smoothness for force production and knee motion is reflective of any overall decline in coordination and control, then it could have implications for likelihood of ACL injury. Future training programs should focus on being addressed with fatigue resistance exercises, while also including movement pattern control training (i.e., feedback) during such fatigue states.

Conclusions

This study was designed to assess the impact fatigue has on the amplitude, variability, and regularity of lower limb kinetics and kinematics during a side-step cutting task. Exercise-induced fatigue led to an overall decrease in mean amplitude and variability (SD) of the ground reaction forces and knee moments post-exercise and a concurrent increase in the pattern of complexity over time (SampEn) GRF for the force profiles, knee kinematics and moments. These results illustrate that fatigue had a differential effect on motor variability, resulting in a both an increase and decrease in the different indices of variability. Thus, the impact of fatigue is not simply restricted to a decline in force producing capacity of the system but also, it leads to an inability to adequately control specific movement dynamics to produce a controlled movement. As the effects of fatigue were restricted to specific variables commonly linked to ACL injury, the implications for these directional changes in pattern variability may provide further insight as to the likelihood of future injury and damage.

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Research Highlights

- The effect of fatigue on variability during a cutting action were assessed
- Exercise-induced fatigue has a differential effect on movement variability
- Variability of ground reaction force and knee moments decreased following fatigue
- Time-dependent measures of variability increased with fatigue
- The increase in signal complexity post-fatigue reflected a decline in coordination

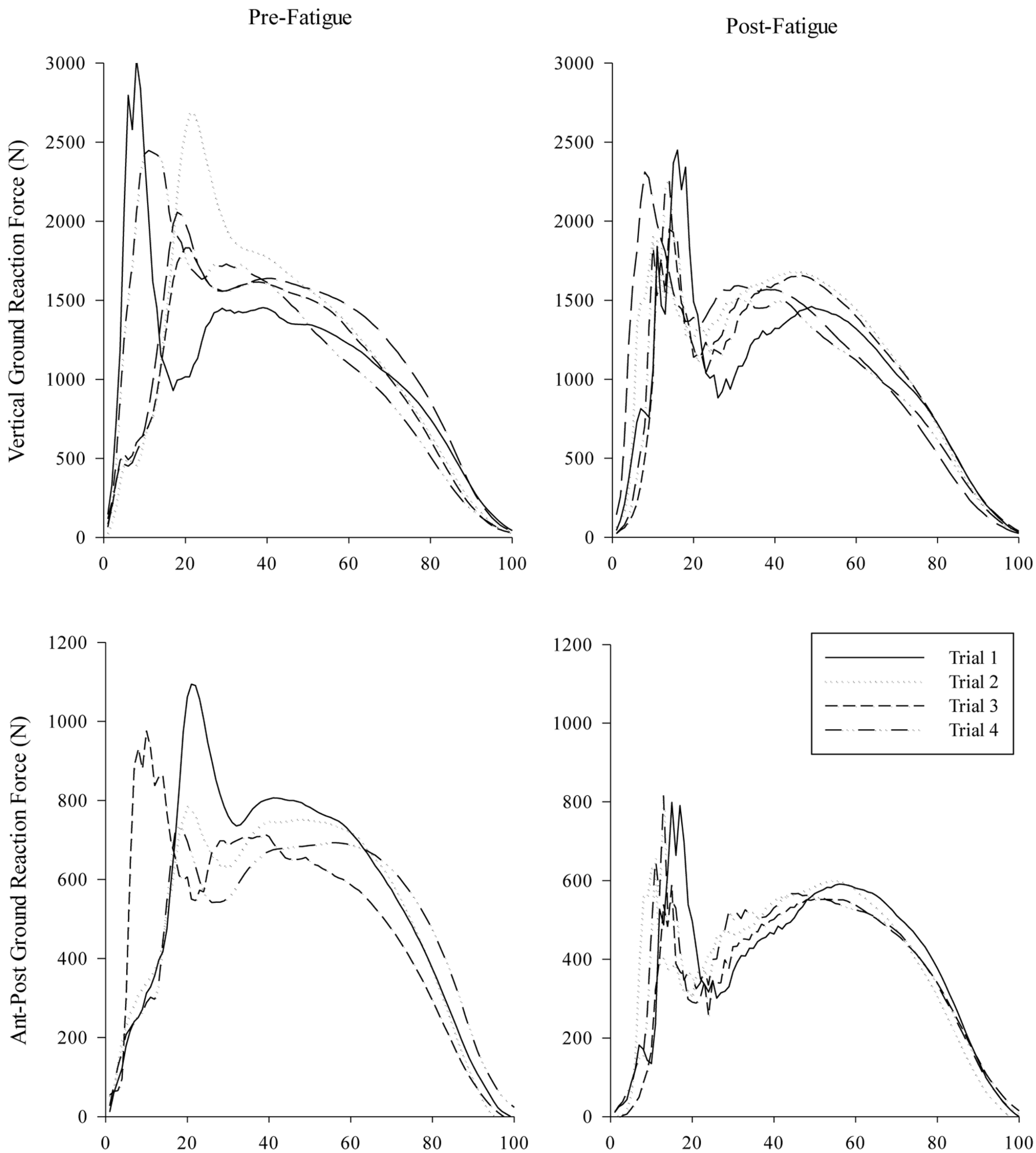

Figure 1.

Representative traces depositing the pattern of ground reaction forces in the vertical and anterior-posterior directions over four successive trials. Traces are shown for a single subject, prior to and after the designated fatigue protocol.

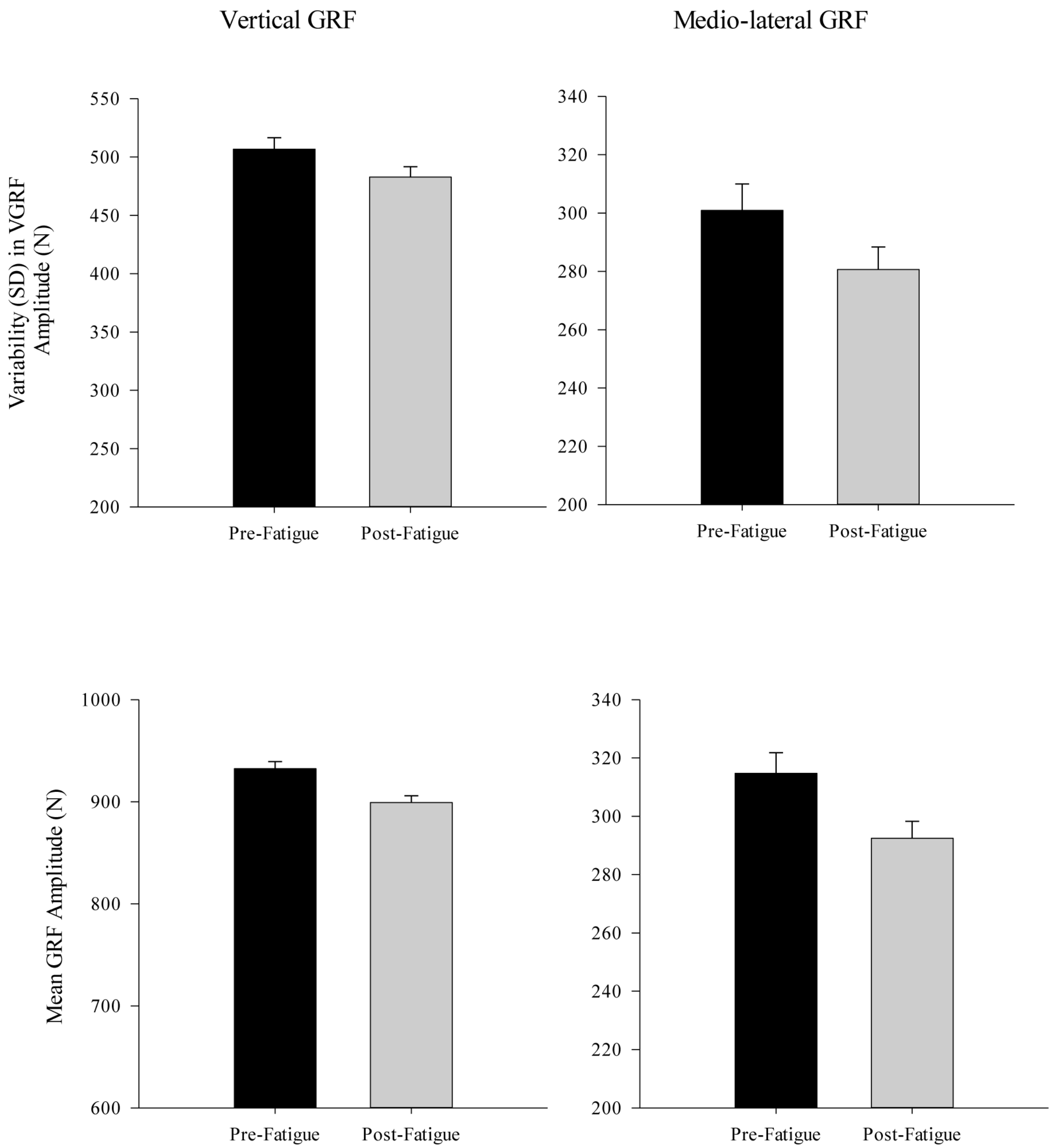

Figure 2.
Differences in mean amplitude and variability (SD) of the vertical and medio-lateral GRFs as a function of the fatigue protocol. Error bars represent one SE of the mean.

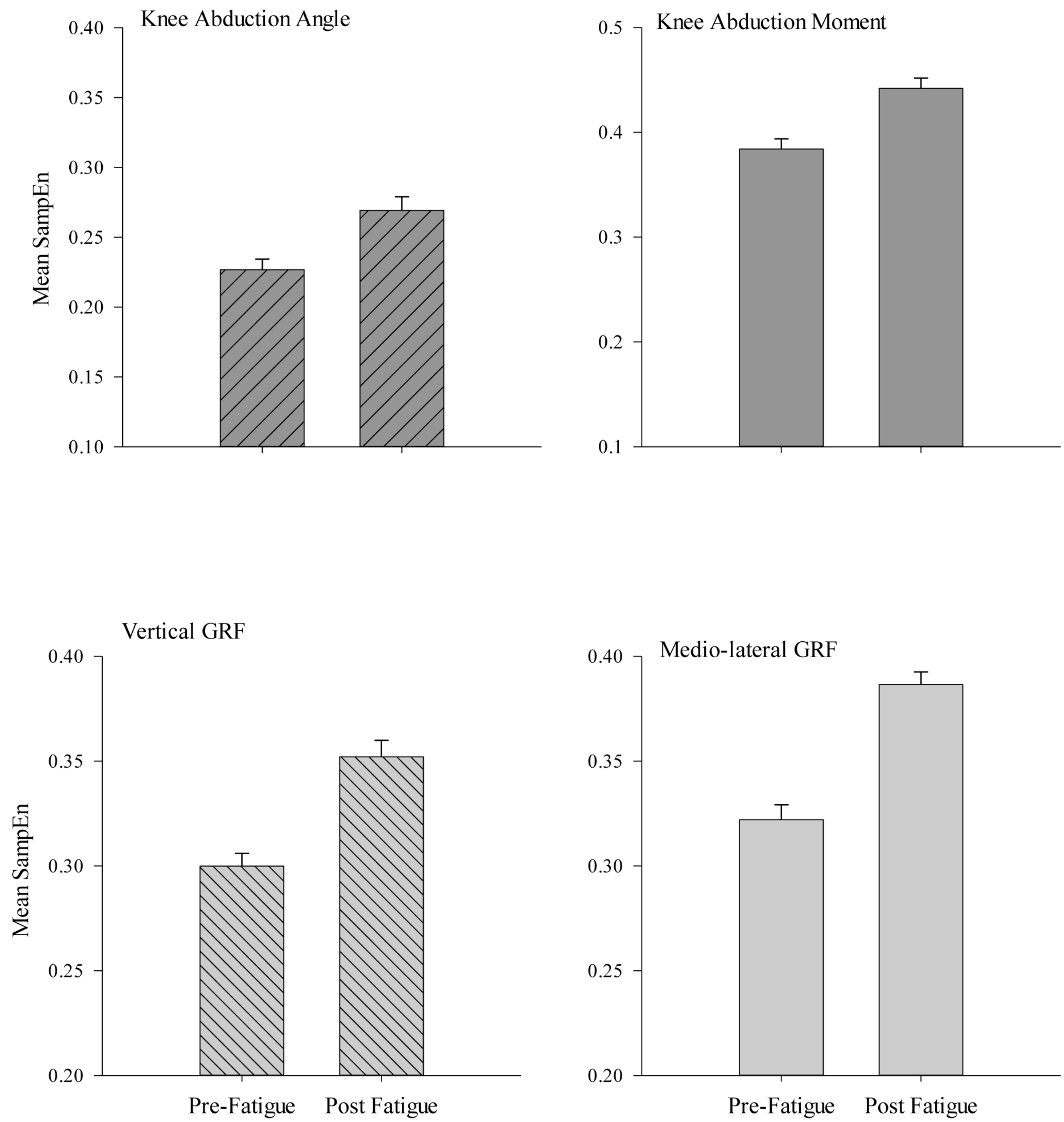

Figure 3.

Changes in average SampEn values for the knee abduction moment, knee abduction angle, vertical GRF and medio-lateral GRF as a function of the fatigue protocol. Error bars represent one SE of the mean.