ANALYSIS OF VARIABILITY IN GROUND REACTION FORCES AND ELECTROMYOGRAPHY FOR RUNNERS OF DIFFERENT ABILITY

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A Thesis
by
WILTON NORRIS

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Abstract

ANALYSIS OF VARIABILITY IN GROUND REACTION FORCES AND ELECTROMYOGRAPHY FOR RUNNERS OF DIFFERENT ABILITY

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Measures of movement variability have been linked to task performance, adaptability, and injury risk. Increasing the understanding of variability in running could be useful in explaining the training adaptations and injury risks of the sport. This study investigated the variability of vertical, antero-posterior, and medio-lateral ground reaction forces and muscle activity of the medial gastrocnemius (Gn), tibialis anterior (TA), rectus femoris (RF), and biceps femoris (BF) between experienced runners (EXP), recreational runners (REC), and non-runners (NON) at five different speeds (2.5 m/s, 3.0 m/s, 3.5 m/s, 4.0 m/s, and 4.5 m/s). It was hypothesized that level of running experience would affect the amount of variability in all three components of ground reaction force (GRF) subjects had at different speeds. This effect between group, speed, and variability did not reach significance for any variables, but the BF muscle appeared to be trending toward significance (p=0.155). This study found that all groups had less variability as speed increased for all three components of ground reaction force, which agreed with previous findings regarding vertical ground reaction force, spatiotemporal, and kinematic measures. This was also the case for activation of the medial gastrocnemius prior to contact. Aside from the BF, we also found that EXP and REC runners did not have different variability for GRF or electromyography (EMG) measures, which disagreed with a previous finding of other muscles. This was likely due to using a higher cutoff of minimum miles run per week run for the REC group than the previous study. Our most interesting finding was

that the variability of the RF prior to contact increased with speed, defying previous findings as well as our own for variables other than muscle activity. This highlights the complex nature of EMG variability during running. Though there seem to be consistent trends in variability measures for spatiotemporal parameters and kinetics, our findings suggest that the interactions between EMG variability, speeds, and group may be more complex and require further investigation.

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Introduction

In recent years, the variability of human movement has been a heavily investigated topic in the fields of both clinical and sport biomechanics (e.g., Hamill, Palmer, & van Emmerik, 2012; Jordan, Challis, Cusumano, & Newell, 2009; Nakayama, Kudo, & Ohtsuki, 2010; Chapman, Vicenzeno, Blanch, & Hodges, 2007; Chapman, Vicenzeno, Blanch, & Hodges, 2008; Fleisig, Chu, Weber, & Andrews, 2009; Gregson, Drust, Atkinson, & Salvo, 2010). It is apparent that movement variability has implications for task performance (Cohen & Sternad, 2009; Fleisig et al., 2009; Nakayama et al., 2010; Chapman et al., 2007; Button, Macleod, Sanders, & Coleman, 2003), motor redundancy (Hamill, van Emmerik, & Heidersheit, 1999; Miller, Meardon, Derrick, & Gillette, 2008), and injury risk (Hamill et al., 1999; van Emmerik & van Wegen, 2000; Bartlett, Wheat, & Robins, 2007; Glazier & Davids, 2009).

Movement variability has traditionally been thought to be an indication of unwanted prediction error in the generation of a movement plan (Fitts, 1954; Fitts & Posner, 1967; Hamill et al., 2012). This is consistent with the term motor invariance, or the existence of optimal movement patterns for a given technique where task specific practice reduces prediction error, resulting in more consistent performance (Stergiou & Decker, 2011). While there is evidence to suggest that higher movement variability may have a detrimental effect on performance (Dierks & Davis, 2007; Knudson & Blackwell, 2005; Salo & Grimshaw, 1998), there is also evidence to suggest that higher variability of coordinated movements could be beneficial to performance (Bartlett et al., 2007; Glazier & Davids, 2009; Hamill et al., 1999). Variability could be considered not only as a manifestation of predictive or random error associated with early stages of motor learning, but also a means for increased adaptability and flexibility to meet constraints, particularly in dynamic performance environments (Hamill et al., 1999; van Emmerik, & van Wegen, 2000; Bartlett et al., 2007; Glazier & Davids, 2009). Furthermore, a number of studies have reported that a certain amount of variability seems to be advantageous in terms of injury, specifically in running overuse injuries injury (Hamill et al., 1999; Heiderscheit, Hamill, & van Emmerik, 2002; Miller et al., 2008; Hamill et al., 2012). It is proposed that, in running, movement variability might attenuate impact shocks from ground reaction forces through the effective distribution of stresses among different tissues (Hamill et al., 1999; Heiderscheit et al., 2002; Hamill et al., 2012).

In addition to the relationship between running related overuse injuries and movement variability, studies have explored how variability is affected by speed as well as how it is impacted by training status. For example, Jordan, Challis, & Newell (2006) found decreases in the variability of vertical ground reaction force and spatiotemporal parameters such as stride interval with increases in speed, but did not compare runners of varying ability. Another, comparing trained and untrained runners, found that trained runners had lower stride interval variability (Nakayama et al., 2010) but failed to find a relationship between variability and speed. Variability of EMG in the leg muscles has also been found to be less in trained vs lesser-trained runners (Chapman et al., 2008), but to our knowledge, has not evaluated across a variety of speeds. Based on this previous research, it therefore appears that trained runners have less variability since they have likely achieved task mastery and developed an optimal movement solution. However, from an injury prevention perspective, it could be argued that having more variability could be advantageous for handling the stresses of high-volume training loads. Furthermore, the actual speeds that elite runners commonly train at tend to be polarized, where most training occurs well below and above anaerobic threshold (Billat, Demarle, & Slawinski, 2001). Given this, it is possible that they exhibit different amount of relative variability across speeds. In comparison, we speculate that the less structured training regiments of less trained runners would result in a narrower range of speeds run in training and therefore, a more consistent relationship between speed and variability. Comparing groups of runners with different training backgrounds over different speeds could provide insight into desirable and undesirable variability of kinetics and EMG in the context of performance.

This study aimed to determine how variability of biomechanical measures, specifically ground reaction force and muscle activation, is affected by distance running experience and running speed. Ground reaction force and lower extremity muscle surface EMG data from three groups of varying levels of running experience were collected at up to seven different speeds on a force plate treadmill. It was thought that the experienced group would have the least amount of variability across all speeds and the recreational group would have more variability than the experienced group but less than the non-running group; this would agree with previous findings that greater running experience results in decreased variability (Nakayama et al., 2010; Chapman et al., 2008). It was also hypothesized that all subjects would have less variability in both EMG and ground reaction forces as speed increases. Further, it was hypothesized that experienced runners will have a smaller decrease in variability than the other groups as speed increases. This hypothesis supports the notion that higher variability would be more beneficial for withstanding stressful training volumes and indicate high flexibility and adaptability to changes in speeds, which are common to elite distance running training (Billat et al., 2001).

Review of Literature

This literature review aims to examine previous research that has explored the variability in running related measures including spatiotemporal parameters, kinetic factors, and EMG of the lower leg muscles. The review will focus on the connection that these variables have with running experience and speed as well any implications that they may have on performance and injury.

Variability and Task Optimization

Human movement variability can be described as the normal variations that occur in motor performance across multiple repetitions of a task (Stergiou, Harbourne, & Cavanaugh, 2006). Movement variability has traditionally been thought to be an indication of unwanted prediction error in the generation of a movement plan that improved with practice (Fitts, 1954; Fitts & Posner, 1967; Hamill et al., 2012). This is consistent with the term motor invariance, or the existence of optimal movement patterns for a given technique (Stergiou & Decker, 2011), where task specific practice reduces prediction error, resulting in more consistent performance. It is clear that the ability to repeat a given movement is influenced by repetitive performance of that movement (Shadmehr & Mussa-Ivaldi, 1994). It is thought that as an individual practices a given task, the internal representation of that movement improves (Shadmehr & Mussa-Ivaldi, 1994), resulting in higher repeatability and decreased dynamic stiffness of that movement (Milner & Cloutier, 1993; Osu et al., 2002; Shadmehr & Mussa-Ivaldi, 1994). This effect of higher repeatability resulting from practice has been observed across a range of tasks such as free throw shooting in basketball (Button et al., 2003), Baseball pitchers (Fleisig et al., 2009), and even basic tasks such as the visual trajectory tracking of elbow flexion and extension (Darling & Cooke, 1987). It is proposed that this decrease in dynamic stiffness results from a decrease in amplitude and duration of muscle activity, greater modulation of muscle activity, and decreased muscle coactivation (Osu et al., 2002; Thoroughman & Shadmehr, 1999). This typically results in an improved performance outcome in addition to a decrease in the variability of movement (Chapman et al., 2007; Chapman et al., 2008; Fujii, Kudo, Ohtsuki, & Oda, 2009; Lee, Swinnen, & Verschueren, 1995; Kudo, Park, Kay, & Turvey, 2006, Tyldesley & Whiting, 1975). This decrease in the variability of movement with practice has been observed in highly repetitive tasks such as cycling (Chapman et al., 2007; Chapman et al., 2008), and running (Nakayama et al., 2010; Chapman et al., 2008).

Variability and Injury

Literature has shown that a large amount of variability present in a specific task can be a manifestation of predictive or random error associated with the early stages of motor learning (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979; Schmidt, Le, & Ilies, 2003; Herzfeld & Shadmehr 2014). There is also much evidence that task specific variability, particularly in running, can be beneficial in terms of reducing the risk of injury (Hamill et al., 1999; Miller et al., 2008). It can also mean increased adaptability and flexibility to meet task specific constraints in dynamic performance environments (Hamill et al., 1999; van Emmerik & van Wegen, 2000; Bartlett, et al., 2007; Glazier & Davids, 2009). It is proposed that, in running, movement variability might attenuate impact shocks from ground reaction forces through the effective distribution of stresses among different tissues (Hamill et al., 1999; Heiderscheit et al, 2002; Hamill et al., 2012). In support of this notion, Hamill, Haddad, Milner, & Davis (2005) found that the coordination variability in the injured limb was significantly less than in the non-injured limb while there was no difference in the level of variability in the limbs of the control subjects. Similarly, Seay, van Emmerik, & Hamill (2011) found that uninjured runners had more coordinative variability of trunk-pelvis transverse plane relations than injured runners suffering from back pain. While it seems that coordinative variability does have a relationship with injury risk, it is still not clear if reduced variability contributes to or results from the injury (Hamill et al., 2012).

Variability Trends in Running

Standard deviation (Jordan, Challis, & Newell, 2007; Seay et al., 2011) and coefficient of variation (CV) (Jordan et al., 2007; Nakayama et al., 2010; Chapman et al., 2008) have been used to quantify the amount of variability present in gait related measures. The more commonly used measure has been CV which is likely because it normalizes the standard deviation of a given measurement to its mean. This allows for the comparison of variability measures that have different means as is the case across different speeds and between individuals.

Although there have been a significant number of studies focusing on the amount of variability of gait cycle parameters across speeds and between populations (i.e. stride interval, step frequency, ground reaction force), in many cases, these studies have yielded contradictory results (Jordan & Newell, 2008; Jordan et al., 2006; Nakayama et al., 2010). Despite this, there has been some consistency in findings for the variability of some variables. It has been found that % CV of spatiotemporal parameters such as stride interval (Jordan et al., 2006), and upper and lower body kinematics (Jordan et al., 2009) tend to have an inverse relationship with running speed, implying that variability decreases with increase in running speed. In a study comparing a range of percentages of preferred running speeds (PRS) for females, Jordan et al., (2007) found that the variability of vertical impulse and peak active vertical ground reaction force also decreased with speed. Though it does appear that the variability of kinematic, spatiotemporal, and some kinetic parameters decrease with speed, this has yet to be confirmed for antero-posterior and medio-lateral ground reaction forces.

Of great interest has been using long ranged coefficients such as DFA (detrended fluctuation analysis) exponent, alpha, to evaluate the time structure of variability across longer durations of running (Jordan et al., 2006, Jordan et al., 2009). These long ranged correlations have revealed a U-shaped time structure of variability across a number of speeds, with the lowest values occurring nearest % preferred running speed (Jordan et al., 2006, Jordan et al., 2009). Jordan et al., (2009) suggests that reduced strength in long ranged correlation at preferred locomotion speeds is reflective of enhanced stability and adaptability at these speeds.

Since surface electromyography signals present a relationship between force produced by the muscle and can be related to the commands of the central nervous system (Milner-Brown & Stein, 1975), it would be thought that EMG variability would follow similar trends to kinetic variability. To our knowledge, the relationship between EMG variability has not been heavily explored; however, van Hedel et al., (2006) found that the Tibialis Anterior muscle appeared to become less variable with speed. This study, however, only used standard deviation to assess EMG variability as opposed to the much more commonly used CV.

Training has also been shown to have an effect on variability of spatiotemporal parameters (Nakayama et al., 2010) as well as EMG (Chapman et al., 2008) for running. Nakayama et al. (2010) compared the variability of mean stride intervals between collegiate runners and non-runners, finding that the collegiate runners had less variability than the non-runners; this study failed to find a relationship between variability and %PRS. It has been proposed that since stabilizing or reducing variability in the stride interval itself is not a task requirement for distance running, this change can be thought of as a byproduct of task-related optimization such as an increase in running economy (Belli, Lacour, Komi, Candau, & Dennis, 1995). Nakayama et al. (2010) stated that learning-related stabilization of stride interval may also improve due to flexible coupling among the neural system, musculoskelatal system, and environment (Taga, Yamaguchi, & Shimizu, 1991; Ohgane, Kazutoshi, & Ohtsuki, 2004), as well as compensatory relationships among task-related parameters (Kudo et al.,, 2000; Latash, Scholz, & Schöner. 2007) or utilization/compensation of interaction torques (Hirashima, Kudo, & Ohtsuki, 2003). Regarding EMG, Chapman et al., (2008) compared the variability of lower extremity muscle recruitment between trained runners, trained triathletes, and less-trained runners. Using root mean squared difference (RMSD) to quantify EMG variability, this study found that less-trained runners were more variable than trained runners for the tibialis anterior, tibialis posterior, gastrocnemius lateralis, and soleus muscles. It should be noted that the less-trained running group only ran an average of 3.4 miles per week whereas the trained group averaged 61.4 miles per week. It could be argued that due to low mileage of the less-trained group, this study more closely compared non-runners to runners rather than two varying groups of runners. This study also only compared data at 4 m/s and did not differentiate between different phases of EMG activity or look at muscles of the thigh. To our knowledge, no studies have compared the variability of EMG between moderately trained runners and highly trained runners across a variety of speeds.

Most relevant to this study, could be the fact that elite runners have specialized training protocols that results in them regularly training at a variety of speeds (Seiler, 2010). Furthermore, the actual speeds that elite runners commonly train at tend to be polarized, given that the majority of training volume consists of either well below the lactate threshold level or above it (Billat et al., 2001). Contrastingly, we speculate that recreational runners are less likely to have as structured training regiments and will likely spend the majority of their training volume at comparatively slower speeds. Given that the repetitive practice of running has been shown to result in decreased variability (Nakayama et al., 2010; Chapman et al., 2008), it could be thought that an individual runner would have the lowest relative variability at speeds regularly performed in training. The findings of Jordan et al. that long ranged correlations of variability tend to be lowest near preferred running speed, which is likely indicative of enhanced stability and adaptability at these speeds (Jordan et al., 2006; Jordan et al., 2009), could give merit to this idea, since runners likely spend the largest part of their training volume running near their preferred speeds. If this were the case, then experienced runners could have relatively lower variability at the absolute speeds well below and above lactate threshold whereas recreational runners may only see this decreased variability at speeds nearest to their preferred running speeds. While more elite runners have been shown to have less variability than less experienced runners (Nakayama et al., 2010; Chapman et al., 2008), they could have comparatively different CV vs. speed relationships than lesser trained runners.

Conclusion

Movement related variability is complex and can have implications with both performance and injury in running. Given their high-volume workload and desired optimal performance, there could be both advantages and disadvantages of altered variability for elite runners. On one hand, reduced variability coinciding with reduced mechanical work at a given speed improves running economy, resulting in better performance. On the other hand, the same decrease in variability as an outcome of repetitive practice and better predictability of movement could theoretically increase the risk of injury. Taking this into account, perhaps the training protocols of elite runners allows them to tolerate such workloads, despite decreased variability, through training across a variety of speeds and varying physical conditions such as running surface and footwear.

Methods

Subjects and Recruitment

Three groups of male subjects, consisting of experienced runners ($n = 10$), recreational runners ($n = 10$), and non-runners ($n = 9$) were recruited for this study. Due to errors in data collection, the results of two subjects were removed, leaving 9 experienced runners, 10 recreational runners, and 8 non-runners. Experienced runners (EXP) were considered individuals between the ages of 18 and 35 that were either currently competing or previously competed at the collegiate level and were actively training for competition. This group included current collegiate (n=3), post collegiate (n=4), and professional athletes (n=3). All participants representing the recreational group also fell between the ages of 18 and 35 and ran an average of 3 or more times per week and greater than 20 miles per week (MPW) for the previous 3 or more years preceding the study. None of the participants in the non-running group (NON) had ever engaged in any type of formal running training. Basic anthropometrics and training history descriptives are shown in Table 1.

Table 1. Participant Anthropometrics and Running Profiles

	Age (yr)	**Height (cm)**	**Mass (kg)**	**BF %**	**Exp (yr)**	**MPW, 3mo (mi)**	**MPW, 3yr (mi)**	**5k PB (min)**
Experienced	24.0±3.4	174.±4.4	61.9±7.0	5.6±2.0	9.5±3.9	69.1±24.1	69.4±21.5	14.6±0.6
Recreational	24.4±5.0	175.8±9.4	68.0±6.9	8.4±4.4	8.6±2.8	31.6±12.4	31.0±11.0	18.3±1.8
Non-runners	22.0±2.4	177.2±4.5	73.7±5.9	11.9±3.5	N/A	N/A	N/A	N/A

BF% = body fat percentage, Exp (yr) = running experience in years, MPW, 3mo = average number of miles run per week for the previous 3 months, MPW, 3yr = average number of miles run per week for the previous 3 years, 5k PB = 5k Personal Best in minutes

Testing Procedure

Prior to testing, subjects were instructed to change into normal running shoes, shorts, and a t-shirt or tank top. The skin surfaces over each muscle of interest were shaved, abraded, and cleaned with an alcohol wipe. Wireless surface EMG electrodes (Delsys Inc., Natick, Massachusetts, USA) were placed on the each of the following muscles on the right leg: rectus femoris, biceps femoris, lateral gastrocnemius, and tibialis anterior. The specific positions of the electrodes were in line with the recommendations provided by seniam.org. The EMG data was be collected using custom Matlab code (Mathworks, Natick, MA, USA).

Next, the subjects were escorted to the isokinetic dynamometer (HUMAC NORM, Stoughton, MA, USA) where they performed maximal isometric contractions of the right leg about the knee and ankle joints in order to measure voluntary isometric contraction EMG data to be used later in analysis. A total of 12 contractions were performed consisting of three trial per contraction type with 15 seconds between trials. Strong verbal encouragement was given for all participants during all trials in a consistent manner. The subjects were situated in an upright seated position at 110 degrees of hip flexion and 70 degrees of knee flexion while three maximal isometric contractions of attempted knee extension were performed. Next, the subjects were situated so that their knees were in complete extension and their ankles flexed at 90 degrees and three maximal contractions of each attempted plantarflexion and dorsiflexion were performed. Lastly, the subjects were situated in a prone position at 45 degrees of knee flexion and performed three contractions of attempted knee flexion.

The participants were then shown to the instrumented treadmill (Bertec, Columbus, OH) and allowed a 3-5 minute warm-up and familiarization period at a speed their own choosing. Upon completion of the warmup, subjects performed up to seven separate running trials on the treadmill. Each trial was a 30 second interval with 2 minutes rest between; the first 15 s served as a familiarization period for the given speed, and the data from seconds 15-25 of each trial was recorded. The subjects were tested at up to seven different speeds, ranging from 2.5 to 4.5 m/s in 0.5 m/s increments; the first four trials of 2.5, 3.0, 3.5, 4.0 m/s were randomized. All subjects managed to complete the 5 speeds and hence, those speeds were used for comparison in analysis. Subjects wore a heart rate monitor and provided feedback on the Borg rate of perceived exertion (RPE) scale after each trial. Subjects were encouraged to discontinue testing upon fatigue.

Data Reduction/Analysis

Only the first 10 steps of the data from 15 to 25 seconds of each 30 second trial were used for processing and analysis. The raw surface EMG data was filtered using a fourth order Butterworth band-pass filter (20 to 400 Hz), rectified, and a linear envelope was created (10 Hz low pass). The EMG variables consisted of average EMG readings as a percentage of maximal voluntary isometric contraction for all four of the lower leg muscles during pre-activation (PA), braking (Br), and propulsion (Pr) at each speed. PA defined as the 50ms prior to contact, and Br and Pr were defined as the readings that coincide with negative and positive anterior-posterior GRF data (shown in Figure 1). The average EMG readings for all three phases were calculated as a percentage of maximal voluntary contraction.

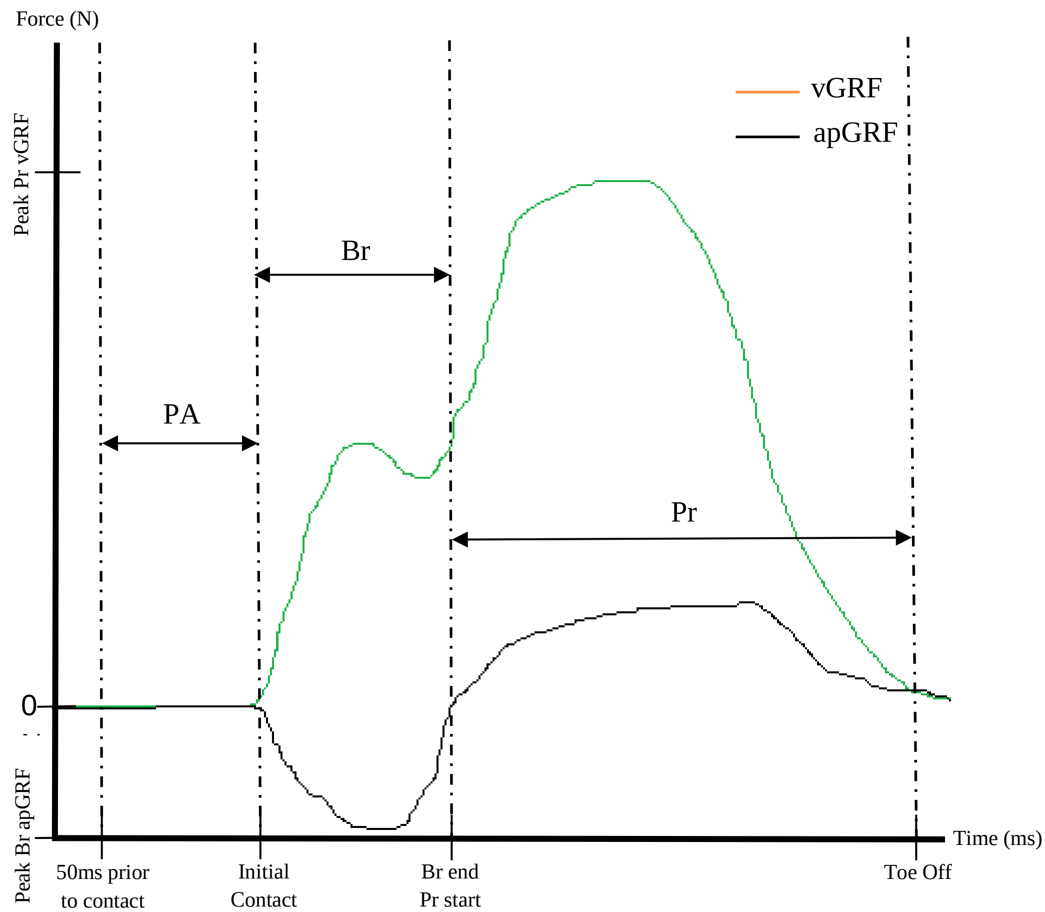

Figure 1. Illustration of the Preactivation (PA), Braking (Br), and Propulsive (Pr) phases

As with the EMG data, the raw force data from 15 to 25 seconds of each trial from the instrumented treadmill were low-pass filtered with a fourth order Butterworth filter at 50 Hz and the first 10 steps selected for further analysis. Then, the average propulsive peak vertical ground reaction force (vGRF), anterior-posterior ground reaction force (apGRF) during braking, and medio-lateral ground reaction force (mlGRF) during stance were calculated.

The outcome variables for each group were calculated by finding the coefficient of variation (CV) of the EMG and GRF variables for each subject (intra-variability) and creating group averages. The formula for CV is shown below.

$$CV = \frac{\sigma}{\mu};\ CV = coefficient\ of\ variation, \sigma = standard\ deviation\ from\ mean;\ \mu = mean$$

The outcome variables for each group consisted of the CV for average preactivation, braking, and propulsive EMG readings (for all four muscles), the average peak propulsive vGRF, peak braking apGRF, and peak mlGRF during stance for all speeds. Aside from its consistent use in a number of other sports related movement variability research (Yang & Winter, 1991; Yang & Winter, 1985; Nakayama et al., 2010; Jordan et al., 2006; Chapman et al., 2008), the CV was selected to quantify variability since it normalized the standard deviation of a given measurement to its mean. The mean normalization of measures was necessary in this study to enable comparison of variability between different populations. A mixed factorial model ANOVA was used to compare differences in the coefficients of variation between groups. For the EMG data, there were three within subjects factors (PA, Br, Pr) and one between subjects factor (group). For the ground reaction force data, there were three within subjects factor (vGRF, apGRF, mlGRF) and one between subjects factor (group). Post hoc analysis was performed using Fisher’s Least Significant Difference.

Results

Prior to statistical analysis, the data was evaluated for outliers. Any subject outcome variables found to be more than 2 standard deviations above the mean were removed, leaving a minimum of 7 subjects per groups for some of the EMG measures. The removed data was dismissed, as it was likely a source of instrumentation error during data collection. Normalized Ground Reaction Force and EMG Data are shown in Tables 2-6.

Table 2. Ground Reaction Force Data Normalized to Body Weight (N/N)

	Group	2.5 m/s	3.0 m/s	3.5 m/s	4.0 m/s	4.5 m/s
vGRF	**EXP**	2.263 ± 0.052	2.377 ± 0.057	2.503 ± 0.048	2.566 ± 0.057	2.624 ± 0.063
	REC	2.313 ± 0.051	2.415 ± 0.059	2.535 ± 0.051	2.613 ± 0.056	2.662 ± 0.065
	NON	2.318 ± 0.054	2.417 ± 0.060	2.540 ± 0.046	2.620 ± 0.054	2.668 ± 0.066
apGRF	**EXP**	0.263 ± 0.022	0.319 ± 0.023	0.379 ± 0.026	0.429 ± 0.029	0.492 ± 0.024
	REC	0.263 ± 0.021	0.317 ± 0.021	0.375 ± 0.025	0.426 ± 0.029	0.487 ± 0.024
	NON	0.261 ± 0.021	0.314 ± 0.020	0.373 ± 0.024	0.424 ± 0.030	0.487 ± 0.023
mlGRF	**EXP**	0.094 ± 0.045	0.122 ± 0.052	0.148 ± 0.065	0.199 ± 0.067	0.221 ± 0.076
	REC	0.087 ± 0.047	0.110 ± 0.053	0.142 ± 0.067	0.194 ± 0.066	0.219 ± 0.078
	NON	0.091 ± 0.047	0.115 ± 0.056	0.148 ± 0.067	0.200 ± 0.068	0.229 ± 0.081

vGRF=Vertical Ground Reaction Force, apGRF=Anterior-posterior Ground Reaction Force, mlGRF=Medio-lateral Ground Reaction Force, EXP=Experienced group, REC=Recreational Group, NON=Non-runner Group

Table 3. Medial Gastrocnemius EMG Data

	Group	2.5 m/s	3.0 m/s	3.5 m/s	4.0 m/s	4.5 m/s
PA	**EXP**	0.050 ± 0.011	0.056 ± 0.012	0.076 ± 0.023	0.078 ± 0.021	0.088 ± 0.020
	REC	0.030 ± 0.008	0.043 ± 0.011	0.052 ± 0.013	0.051 ± 0.013	0.062 ± 0.014
	NON	0.046 ± 0.008	0.046 ± 0.009	0.051 ± 0.011	0.049 ± 0.011	0.046 ± 0.009
Br	**EXP**	0.226 ± 0.043	0.287 ± 0.062	0.336 ± 0.072	0.384 ± 0.066	0.449 ± 0.070
	REC	0.214 ± 0.038	0.220 ± 0.063	0.291 ± 0.054	0.334 ± 0.053	0.338 ± 0.056
	NON	0.153 ± 0.030	0.163 ± 0.039	0.184 ± 0.043	0.229 ± 0.038	0.248 ± 0.051
Pr	**EXP**	0.525 ± 0.063	0.587 ± 0.068	0.631 ± 0.089	0.685 ± 0.104	0.757 ± 0.087
	REC	0.627 ± 0.098	0.708 ± 0.087	0.760 ± 0.093	0.778 ± 0.096	0.931 ± 0.147
	NON	0.478 ± 0.055	0.498 ± 0.062	0.557 ± 0.063	0.561 ± 0.075	0.648 ± 0.090

PA=Preactivity Phase, Br=Braking Phase, Pr=Propulsive Phase, EXP=Experienced group, REC=Recreational Group, NON=Non-runner Group

Table 4. Tibialis Anterior EMG Data

	Group	2.5 m/s	3.0 m/s	3.5 m/s	4.0 m/s	4.5 m/s
	EXP	0.113 ± 0.017	0.112 ± 0.018	0.114 ± 0.018	0.163 ± 0.026	0.136 ± 0.026
PA	**REC**	0.113 ± 0.022	0.121 ± 0.020	0.134 ± 0.022	0.158 ± 0.029	0.162 ± 0.032
	NON	0.122 ± 0.025	0.132 ± 0.023	0.139 ± 0.027	0.178 ± 0.030	0.192 ± 0.032
	EXP	0.147 ± 0.023	0.191 ± 0.035	0.210 ± 0.034	0.361 ± 0.062	0.289 ± 0.054
Br	**REC**	0.184 ± 0.031	0.219 ± 0.035	0.261 ± 0.039	0.299 ± 0.041	0.327 ± 0.043
	NON	0.179 ± 0.025	0.217 ± 0.045	0.238 ± 0.036	0.308 ± 0.041	0.350 ± 0.053
	EXP	0.060 ± 0.009	0.063 ± 0.010	0.090 ± 0.014	0.164 ± 0.031	0.215 ± 0.033
Pr	**REC**	0.058 ± 0.010	0.085 ± 0.018	0.131 ± 0.024	0.130 ± 0.025	0.126 ± 0.022
	NON	0.062 ± 0.008	0.084 ± 0.012	0.086 ± 0.018	0.123 ± 0.024	0.223 ± 0.043

PA=Preactivity Phase, Br=Braking Phase, Pr=Propulsive Phase, EXP=Experienced group, REC=Recreational Group, NON=Non-runner Group

Table 5. Rectus Femoris EMG Data

	Group	2.5 m/s	3.0 m/s	3.5 m/s	4.0 m/s	4.5 m/s
	EXP	0.114 ± 0.016	0.104 ± 0.017	0.107 ± 0.023	0.107 ± 0.021	0.103 ± 0.020
PA	**REC**	0.014 ± 0.005	0.016 ± 0.004	0.021 ± 0.005	0.035 ± 0.014	0.042 ± 0.019
	NON	0.021 ± 0.005	0.023 ± 0.006	0.029 ± 0.013	0.035 ± 0.019	0.033 ± 0.009
	EXP	0.113 ± 0.021	0.094 ± 0.021	0.095 ± 0.019	0.143 ± 0.025	0.142 ± 0.022
Br	**REC**	0.057 ± 0.012	0.062 ± 0.014	0.062 ± 0.012	0.074 ± 0.024	0.092 ± 0.025
	NON	0.088 ± 0.016	0.083 ± 0.012	0.094 ± 0.014	0.108 ± 0.020	0.112 ± 0.027
	EXP	0.171 ± 0.048	0.234 ± 0.056	0.258 ± 0.053	0.276 ± 0.045	0.311 ± 0.061
Pr	**REC**	0.142 ± 0.036	0.226 ± 0.040	0.245 ± 0.047	0.338 ± 0.075	0.403 ± 0.077
	NON	0.143 ± 0.026	0.175 ± 0.024	0.213 ± 0.035	0.249 ± 0.042	0.303 ± 0.041

PA=Preactivity Phase, Br=Braking Phase, Pr=Propulsive Phase, EXP=Experienced group, REC=Recreational Group, NON=Non-runner Group

Table 6. Biceps Femoris EMG Data

	Group	2.5 m/s	3.0 m/s	3.5 m/s	4.0 m/s	4.5 m/s
	EXP	0.243 ± 0.034	0.227 ± 0.032	0.261 ± 0.031	0.251 ± 0.036	0.340 ± 0.172
PA	**REC**	0.157 ± 0.025	0.167 ± 0.023	0.168 ± 0.029	0.866 ± 0.366	0.158 ± 0.027
	NON	0.109 ± 0.021	0.188 ± 0.224	0.124 ± 0.036	0.194 ± 0.140	0.145 ± 0.041
	EXP	0.231 ± 0.039	0.259 ± 0.047	0.308 ± 0.052	0.340 ± 0.057	0.363 ± 0.058
Br	**REC**	0.183 ± 0.035	0.207 ± 0.036	0.231 ± 0.035	1.192 ± 0.169	0.279 ± 0.045
	NON	0.212 ± 0.036	0.260 ± 0.041	0.280 ± 0.042	0.331 ± 0.049	0.379 ± 0.056
	EXP	0.350 ± 0.064	0.432 ± 0.108	0.626 ± 0.162	0.732 ± 0.127	0.827 ± 0.153
Pr	**REC**	0.141 ± 0.029	0.175 ± 0.044	0.204 ± 0.051	1.247 ± 0.573	0.311 ± 0.064
	NON	0.289 ± 0.058	0.335 ± 0.062	0.389 ± 0.073	0.439 ± 0.076	0.518 ± 0.118

PA=Preactivity Phase, Br=Braking Phase, Pr=Propulsive Phase, EXP=Experienced group, REC=Recreational Group, NON=Non-runner Group

CV of Ground Reaction Forces

Coefficients of Variation for v, ap, and ml GRF are shown in Figure 2. No significant 3-way interaction effect was detected for Group × GRF × Speed ($F_{5.395,53.954} = 0.571, p = 0.735, \eta 2 = 0.054$).

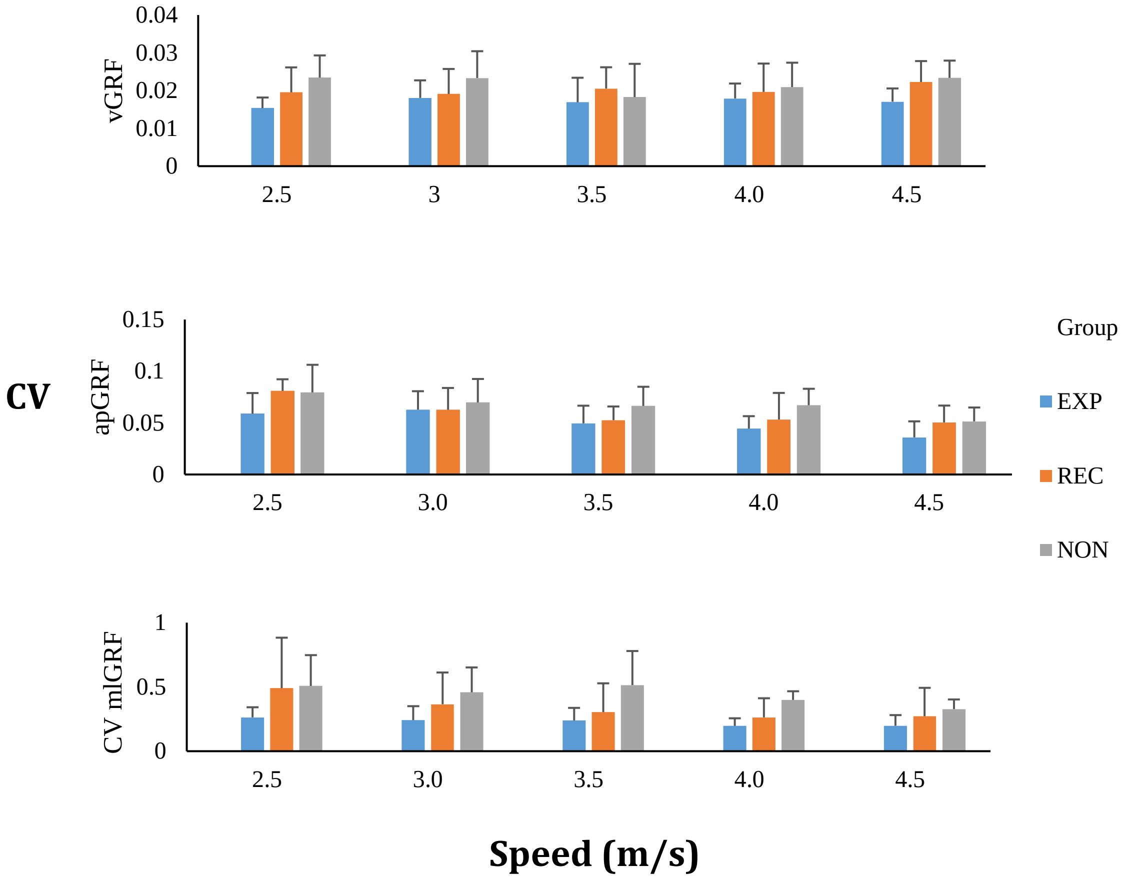

Figure 2. CV of Ground Reaction Forces for the v, ap, ml Components. No significant 3-way interaction effect of Group × GRF × Speed was found.

A significant GRF × Group interaction effect was observed ($F_{2.021,20.21} = 6.029, p = 0.009, \eta 2 = 0.376$) and is shown in Figure 3. Pairwise comparisons revealed for v, ap, and ml components of GRF (regardless of speed), EXP had lower CV than NON ($p < 0.05$) and, for mlGRF, REC had lower CV than NON ($p < 0.05$); there were no significant differences between EXP and REC for any GRF conditions. Pairwise comparisons also revealed that for all groups, the CV of vGRF was less than both the CV of apGRF and mlGRF ($p < 0.001$) and the CV of apGRF was less than the CV of mlGRF ($p < 0.001$).

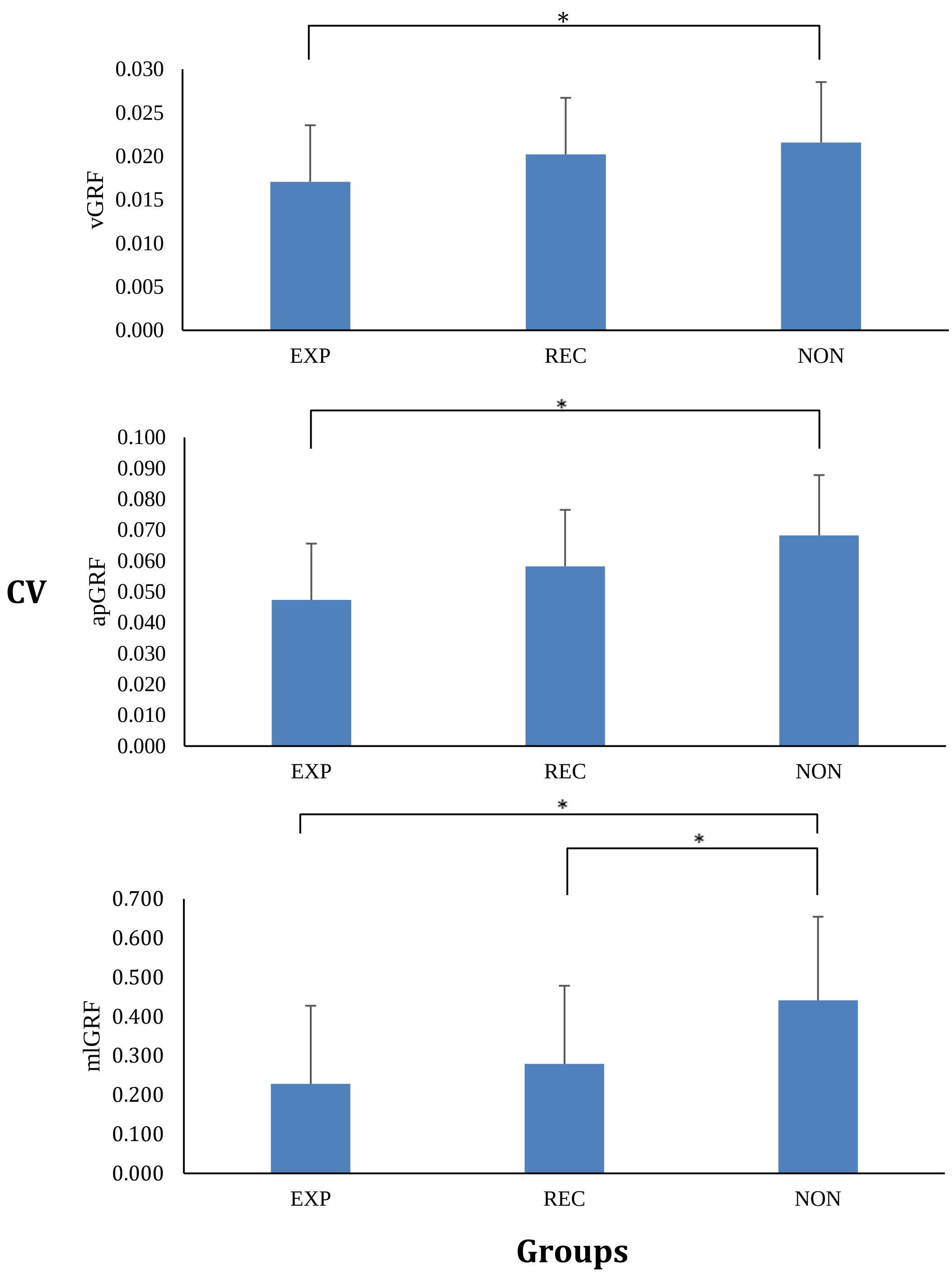

Figure 3. Differences in CV for GRF between EXP, REC, and NON. * significant difference among groups

A significant GRF × Speed interaction effect was also observed ($F_{2.698,53.95} = 6.799, p = 0.001, \eta 2 = 0.254$) and is shown in Figure 4. Pairwise comparisons showed that for apGRF the CV of 2.5 m/s was greater than all other speeds ($p < 0.05$), 3.0 m/s was greater than 4.5 m/s ($p < 0.05$) but not different from 4.0 m/s, and 4.0 m/s was greater than 4.5 m/s ($p < 0.05$). For mlGRF, the CV of 2.5 m/s was greater than 4.0 m/s and 4.5 ($p < 0.05$), 3.0 m/s was greater than 4.0 m/s and 4.5 m/s ($p < 0.05$), 3.5 m/s was greater than 4.0 m/s and 4.5 m/s ($p < 0.05$), and 4.0 m/s was greater than 4.5 m/s ($p < 0.05$). Pairwise comparisons also showed that for all speeds, the CV of vGRF was lower than both apGRF and mlGRF ($p < 0.001$) and the CV of apGRF was less than the CV of mlGRF ($p < 0.001$).

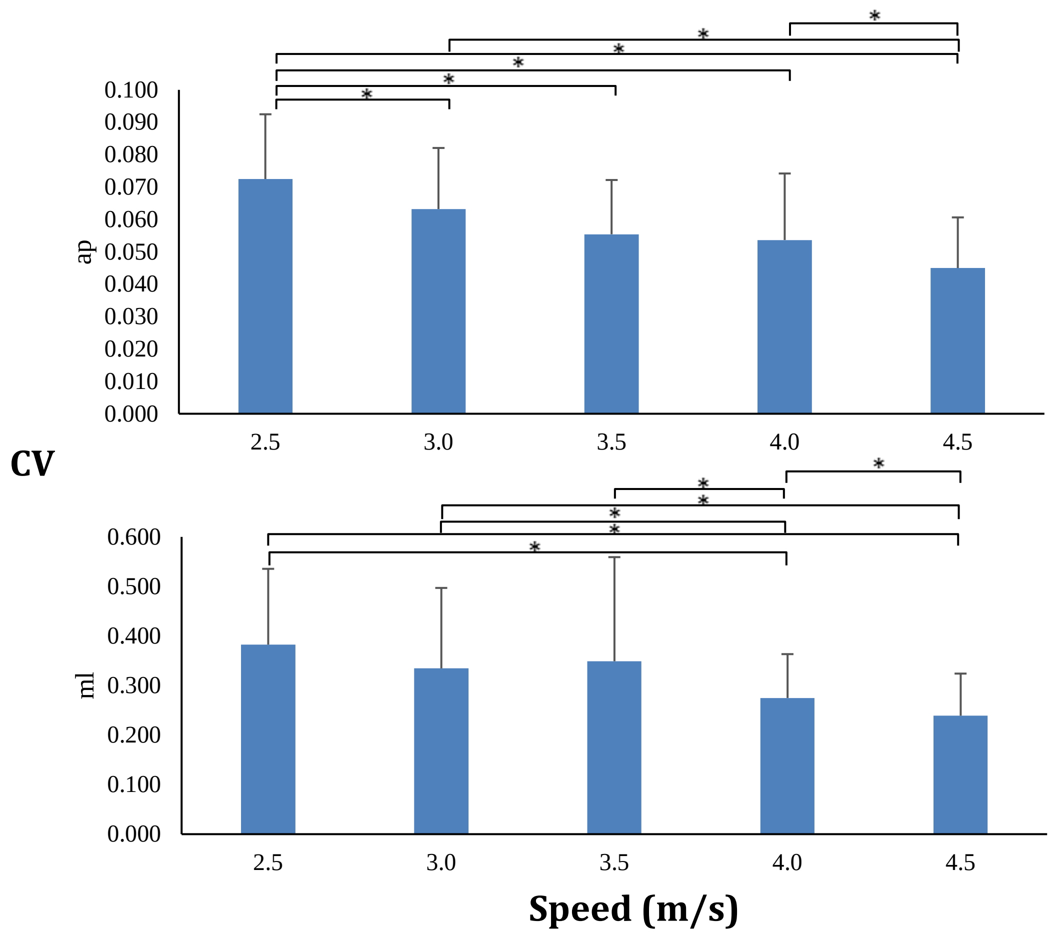

Figure 4. Differences Between Speeds of CV for GRF. * significant difference (P<0.05) among speeds

CV of the medial Gn

Coefficients of Variation for PA, Br, and Pr phases of the medial gastrocnemius (Gn) are shown in Figure 5. No significant 3-way interaction effect was detected for Group × Phase × Speed ($F_{9.417,94.714} = 1.124, p = 0.337, \eta 2 = 0.101$).

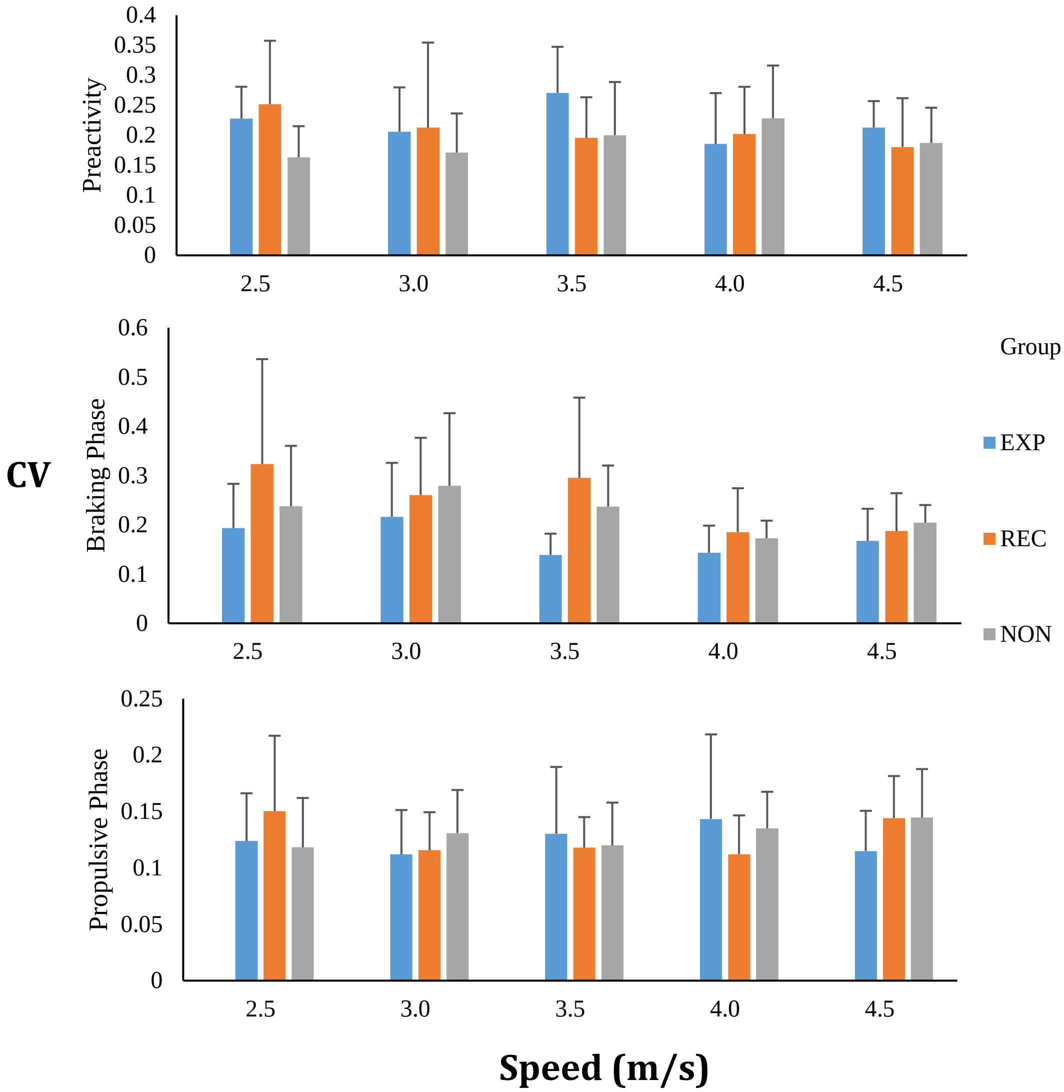

Figure 5. CV of the Medial Gastrocnemius. No significant 3-way interaction effect of Group × Phase × Speed was found.

A significant Speed × Phase interaction effect was observed ($F_{4.736,94.714} = 2.952, p = 0.018, \eta 2 = 0.129$) and is shown in Figure 6. Pairwise comparisons showed that for PA, CV for 2.5

m/s was greater than 4.0 m/s ($p < 0.05$) and 4.5 ($p < 0.05$), 3.0 m/s was greater than 4.0 m/s ($p < 0.05$) and 4.5 m/s ($p < 0.05$), 3.5 m/s was greater than 4.0 m/s ($p < 0.05$) but not 4.5 m/s ($p = 0.05$), and 4.0 m/s and 4.5 m/s were not different ($p = 0.263$). Pairwise comparisons also showed that for all speeds, CV for PA and Br did not differ from one another but both were greater than Pr ($p < 0.01$).

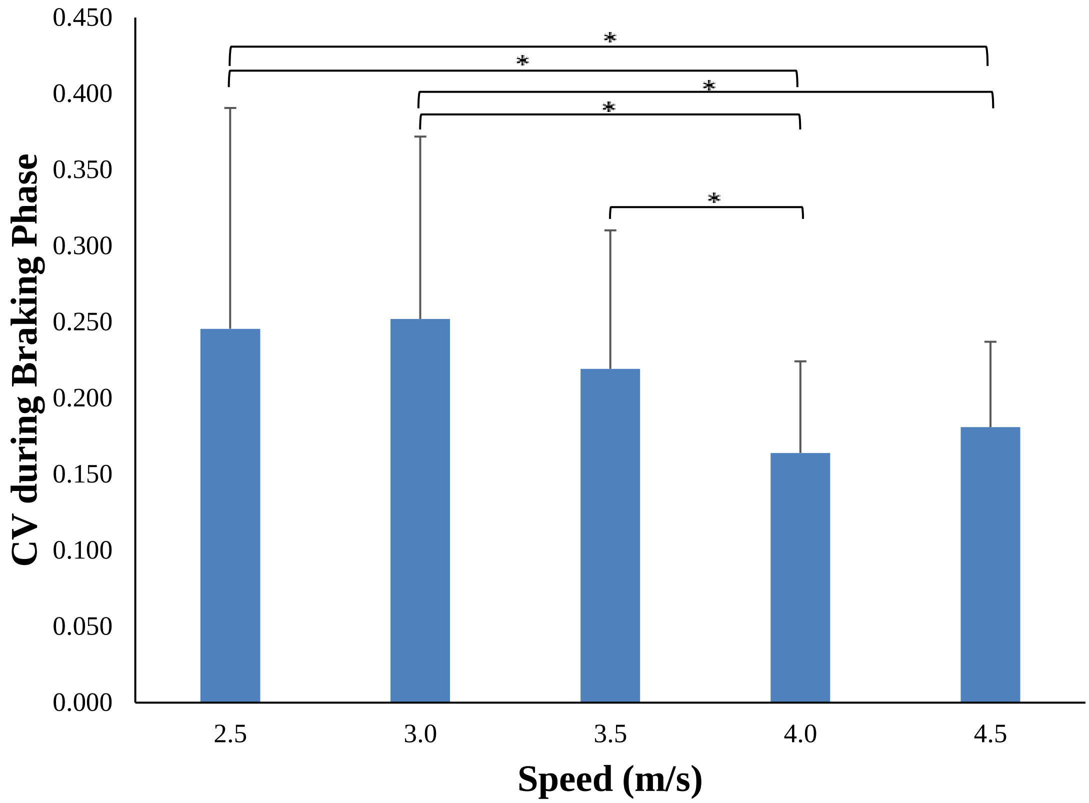

Figure 6. Differences Between Speeds of CV for the Medial Gastrocnemius during Braking.* significant difference (P<0.05) among speeds

There were no significant interaction effects for Phase × Group ($F2.455,24.544 = 1.255, p = 0.304, \eta 2 = 0.112$) or Speed × Group ($F_{6.211,62.123} = 1.392, p = 0.23, \eta 2 = 0.122$). There was also no main effect of Group ($F_{2,20} = 1.487, p = 0.25, \eta 2 = 0.129$).

CV of the TA

Coefficients of Variation for PA, Br, and Pr phases of the tibialis anterior (TA) are shown in Figure 7. No significant 3-way interaction effect was detected for Group × Phase × Speed ($F_{9.402,94.024} = 0.46, p = 0.904, \eta 2 = 0.044$). There were also no interaction effects for Phase × Group ($F_{3.128,31.277} = 0.295, p = 0.837, \eta 2 = 0.029$), Speed × Phase ($F_{4.701,94.024} = 0.700, p = 0.616, \eta 2 = 0.034$), or Speeds × Group ($F_{6.257,62.573} = 0.541, p = 0.782, \eta 2 = 0.051$).

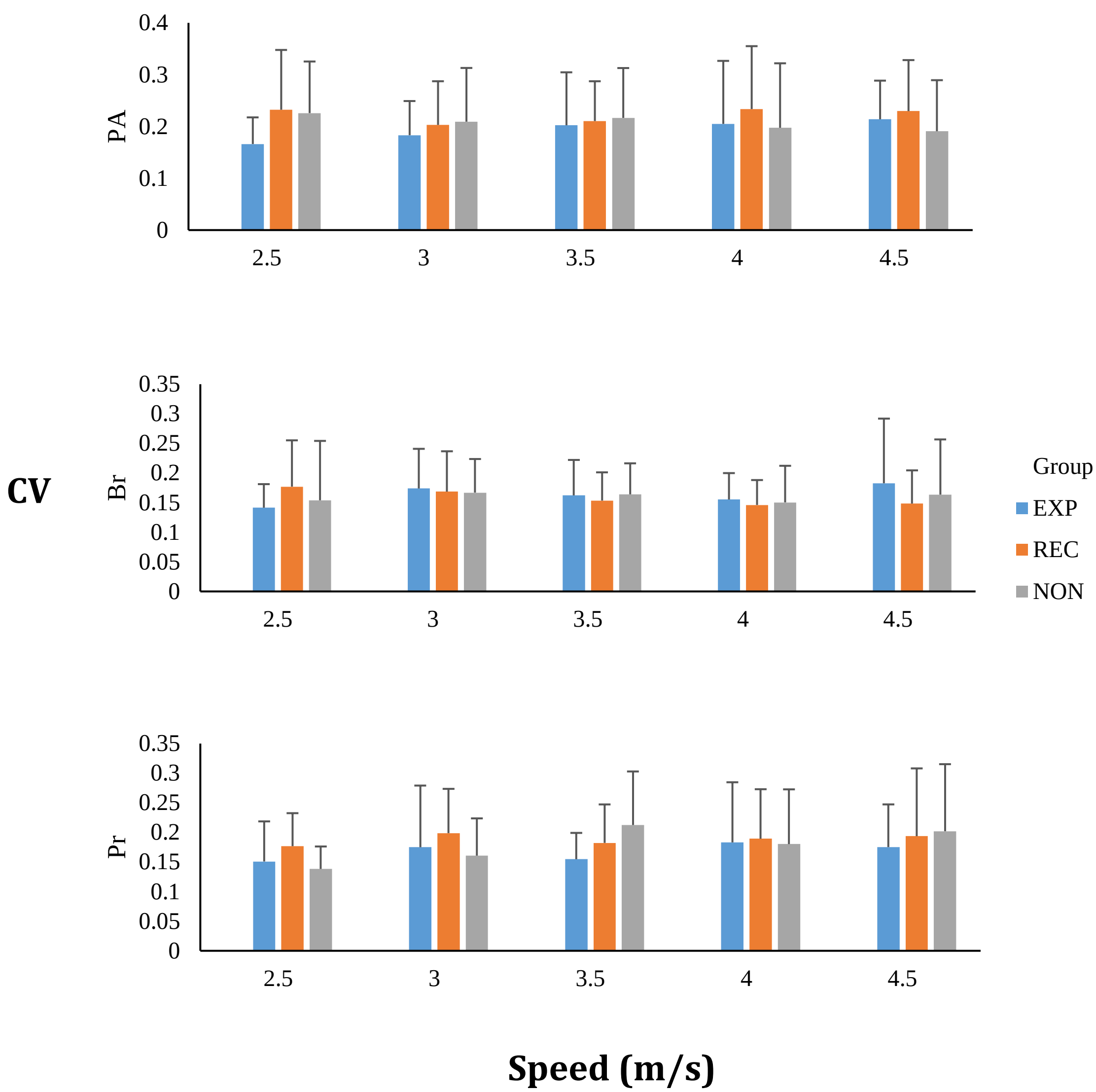

Figure 7. CV of the Tibialis Anterior. No significant 3-way interaction effect of Group × Phase × Speed was found.

There were no main effects of Group ($F_{2,20} = 0.08, p = 0.924, \eta 2 = 0.008$) or Speed ($F_{4,80} = 0.721, p = 0.58, \eta 2 = 0.035$), but a main effect was found for Phase ($F_{1.564,31.277} = 4.482, p = 0.027, \eta 2 = 0.183$) and is shown in Figure 8. Pairwise comparisons showed that, regardless of group or speed, CV for PA was greater than Br ($p < 0.01$) but not different from Pr ($p = 0.263$) and that Br and Pr were not different ($p = 0.107$).

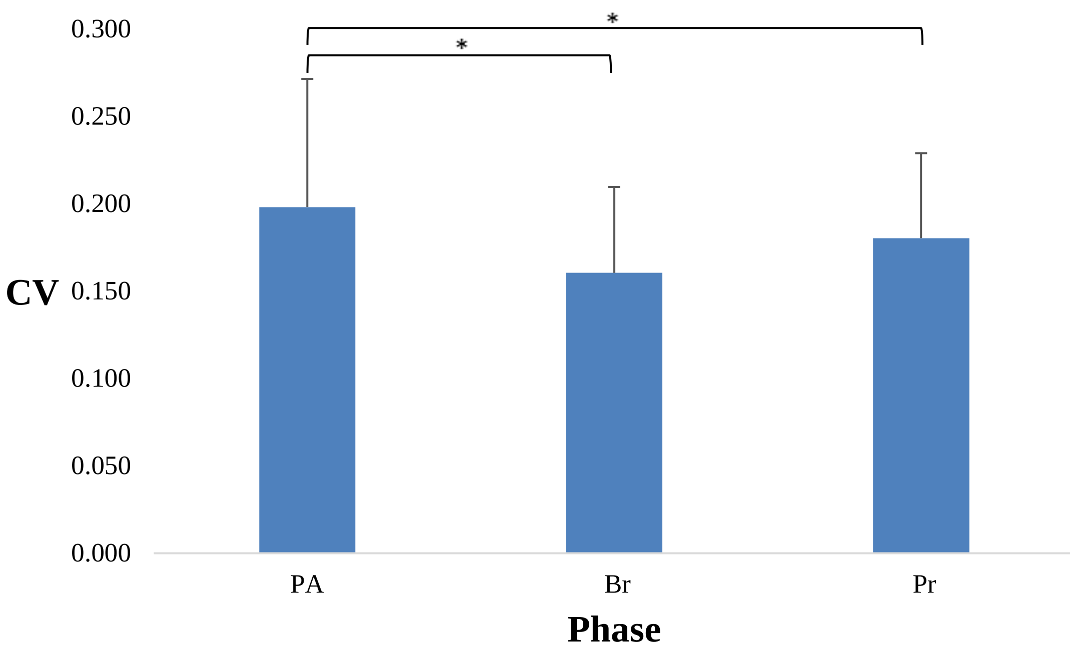

Figure 8. Differences Between Phases of CV for the Tibialis Anterior. * significant difference (P<0.05) among phases

CV of the RF

Coefficients of Variation for PA, Br, and Pr phases of the rectus femoris (RF) are shown in Figure 9. No significant 3-way interaction effect was detected for Group × Phase × Speed ($F_{5.964,50.694} = 1.235, p = 0.249, \eta 2 = 0.127$).

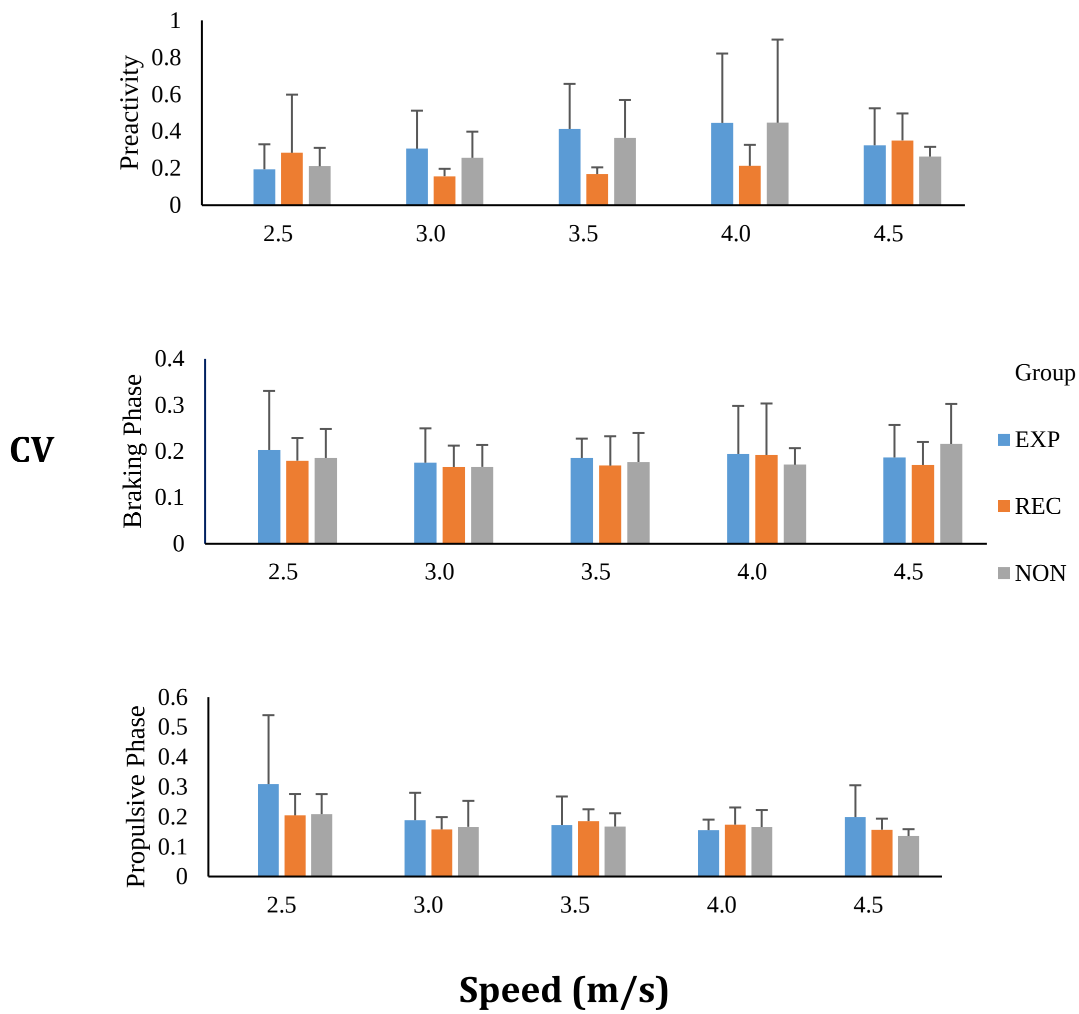

Figure 9. CV of the Rectus Femoris. No significant 3-way interaction effect of Group × Phase × Speed was found.

A significant Speed × Phase interaction effect was observed ($F_{2.982,50.694} = 3.219, p = 0.031, \eta 2 = 0.159$) and is shown is Figure 10. Pairwise comparisons showed that for PA, CV of 2.5 m/s was less than 3.5 m/s ($p < 0.01$), 4.0 m/s ($p < 0.05$), and 4.5 m/s ($p < 0.01$); CV of 3.0 m/s was less than 4.5 m/s ($p < 0.05$); and CV of 3.5 m/s, 4.0 m/s, and 4.5 m/s were not different; for Br and Pr, there no differences in CV between speeds. Pairwise comparisons also showed that for 2.5 m/s and 3.0 m/s, there were no differences in CV between PA, Br, or Pr; for 3.5 m/s and 4.0 m/s, CV of PA was greater than Br ($p < 0.05$) and Pr ($p < 0.05$) and Br and Pr were not different; for 4.5 m/s, CV of PA was greater than both Br ($p < 0.05$) and Pr ($p < 0.05$), and Br was greater than Pr ($p < 0.05$).

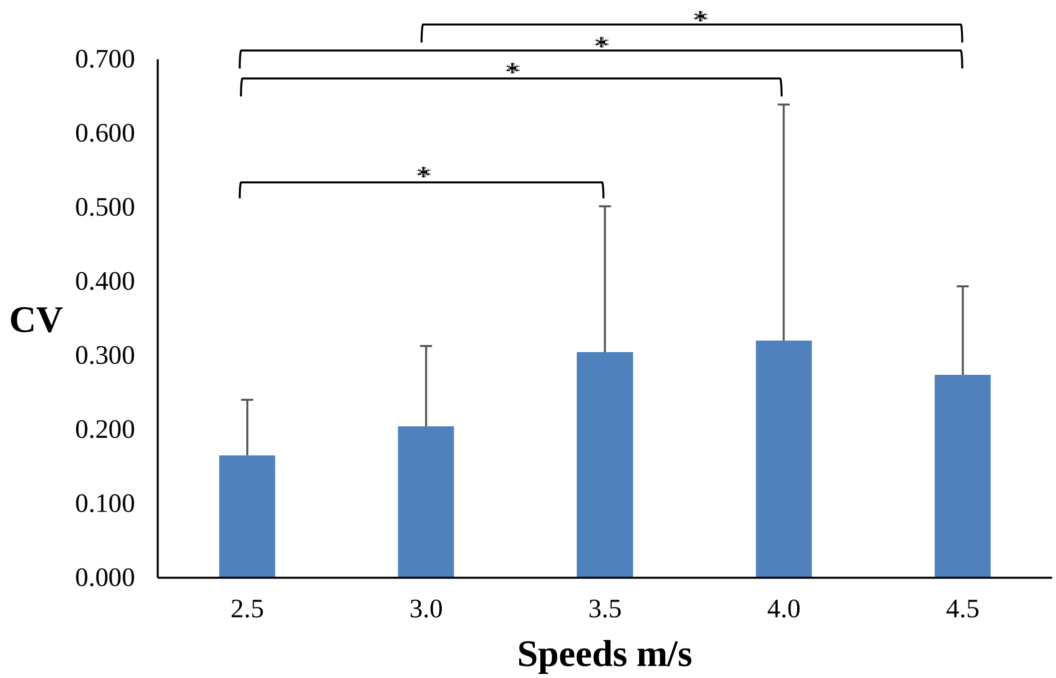

Figure 10. Differences Between Speeds of CV for the Rectus Femoris during Preactivation. * significant difference (P<0.05) among speeds

There were no significant interaction effects for Speeds × Group ($F_{4.842,41.159} = 0.87, p = 0.507, \eta 2 = 0.93$) or Time × Group ($F_{2.881,24.491} = 1.42, p = 0.261, \eta 2 = 0.143$). No main effect of Group was detected ($F_{2,17} = 1.894, p = 0.181, \eta 2 = 0.182$).

CV of the BF

Coefficients of Variation for PA, Br, and Pr phases of the biceps femoris (BF) are shown in Figure 11. No significant 3-way interaction effect was detected for Group × Phase × Speed ($F_{8.369,83.687} = 1.532, p = 0.155, \eta 2 = 0.133$).

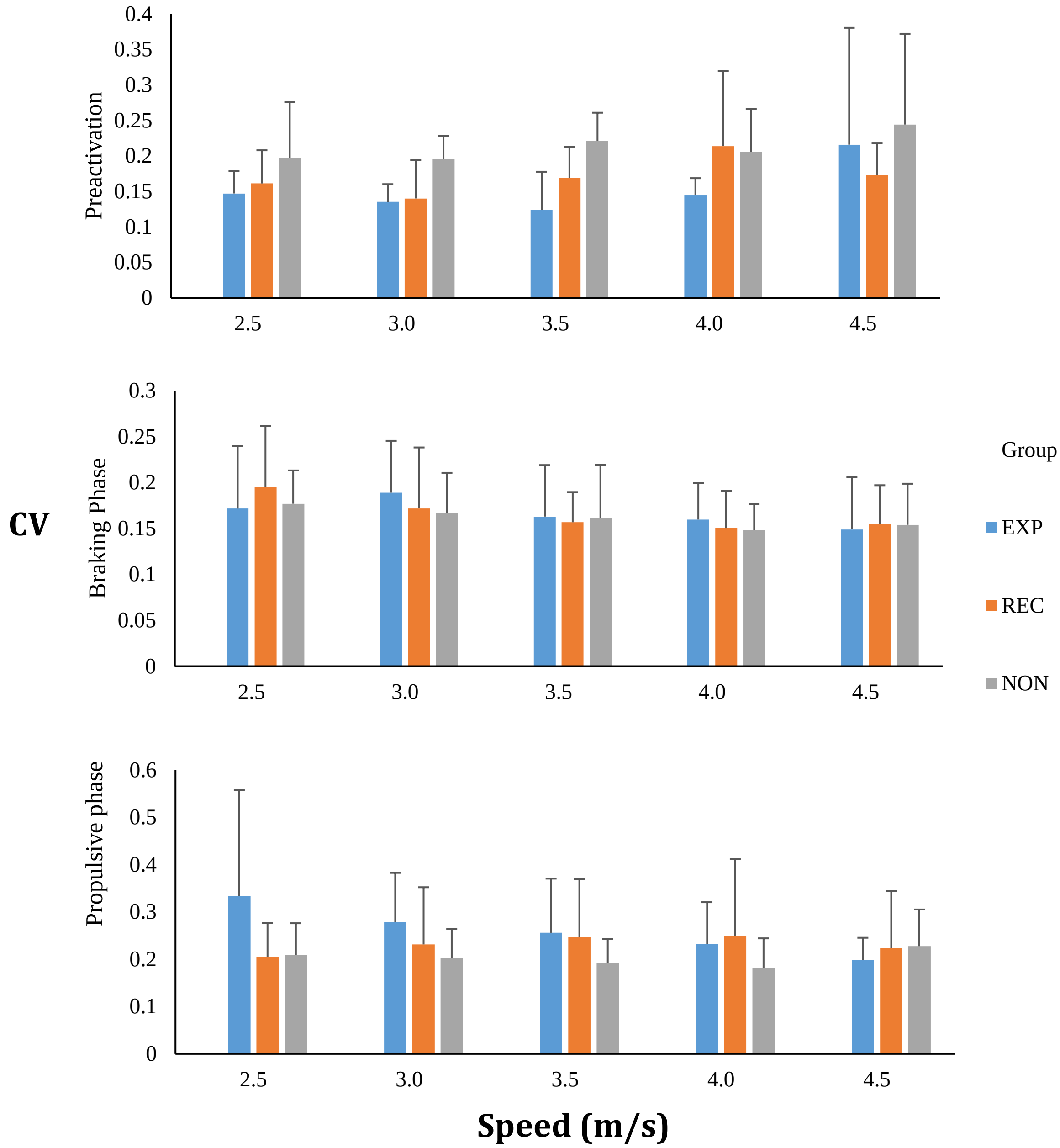

Figure 11. CV of the Biceps Femoris. No significant 3-way interaction effect of Group × Phase × Speed was found.

A significant Phase × Group interaction effect was observed ($F_{2.803,28.031} = 4.404, p = 0.013, \eta 2 = 0.306$) and is shown in Figure 12. Pairwise comparisons showed that for PA, EXP had lower CV than REC ($p < 0.05$) and NON ($p < 0.001$) and REC had lower CV than NON ($p <$

0.01); there no were no differences in CV between groups for Br or Pr. Pairwise comparisons also showed that for EXP and REC, CV of PA and Br were both less than Pr ($p < 0.05$) but did not different from one another.

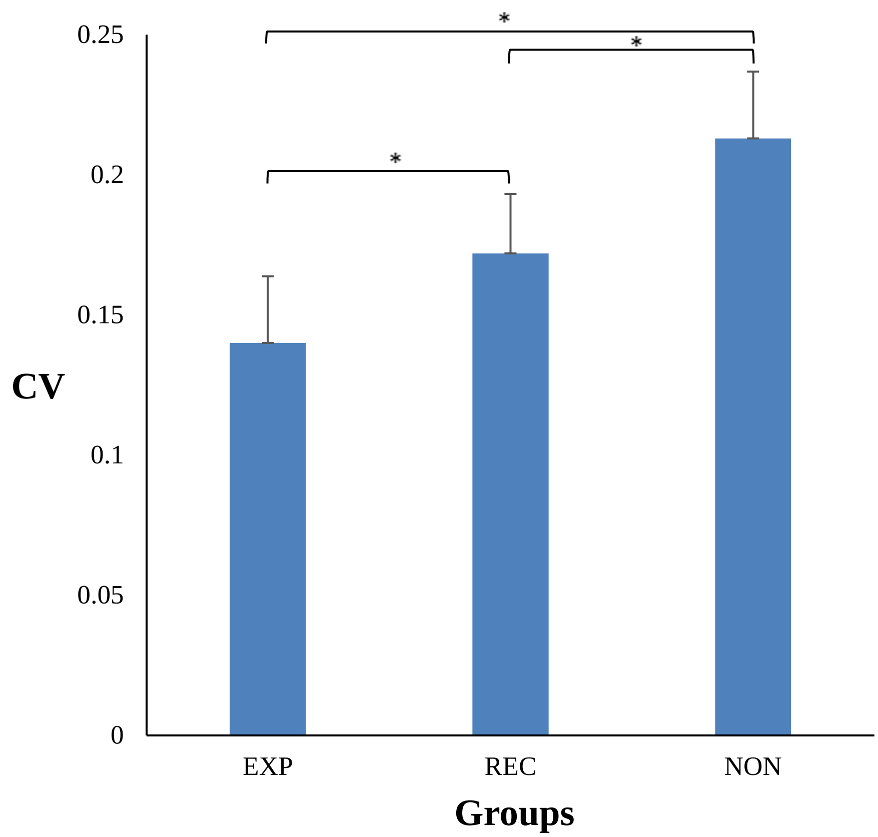

Figure 12. Differences Between Groups of CV for the Biceps Femoris during Preactivation. * significant difference (P<0.05) among groups.

There were no significant interaction effects for Speed × Time ($F_{4.184,83.687} = 1.677, p = 0.16, \eta 2 = 0.077$) or Speed × Group ($F_{6.024,60.239} = 0.701, p = 0.651, \eta 2 = 0.065$). No main interaction effect of Speed was found ($F_{3.012,60.239} = 0.36, p = 0.783, \eta 2 = 0.018$).

Discussion

In this study, experienced runners, recreational runners, and non-runners ran on a Bertec instrumented treadmill at a minimum of 5 different speeds, ranging from 2.5 m/s to 4.5 m/s while ground reaction forces in the v, ap, and ml directions as well as EMG data for the medial Gn, TA, RF, and BF were collected. This study sought to investigate whether all three components of ground reaction force (v, ap, ml) and EMG variability of four leg muscles (Gn, TA, RF, BF) not only followed similar trends to previous findings (Jordan et al., 2006; Jordan et al., 2007; Nakayama et al., 2010; Chapman et al., 2008), but if there was a three way interaction effect between variability, training status, and speed. This study explored if there were variability differences between sub-populations of runners (ie. Experienced vs. Recreational vs. Non-runners) using stricter training history selection criteria than that traditionally used in previous studies (Chapman et al., 2008; Nakayama et al., 2010).

This study found no influence of group on the variability of ground reaction forces or EMG as speed increased; however, the BF muscle did appear to be trending toward significance ($p = 0.155$). Though this does not suggest statistical significance, it cannot be ruled out that this relationship exists. This certainly calls for further investigation of a potential 3-way interaction effect of the BF muscle. This study did find significant interactions between variability and speed as well as between variability and group. Variability for peak apGRF, mlGRF, and average EMG of the Gn during braking appeared to decrease as subjects ran at higher speeds. This aligns with previous research on running that supports a decrease in variability with speed (Jordan et al., 2006, Jordan et al., 2009). We also found a relationship between variability of all three components and group, where the EXP and REC groups had less variability than the NON group but were not different from one another. Unexpectedly, the variability of the average EMG for the RF during PA increased with speed. While no relationship between variability of average EMG and speed was found for the BF, we did find a relationship between variability and group during PA where greater experience resulted in less variability, regardless of speed (EXP<REC<NON). This agreed with previous findings that greater running experience results in decreased CV (Nakayama et al., 2010; Chapman et al., 2008)

Ground Reaction Force Variability and Speed

This study found that the variability ap and ml GRF decreased as speed increased, but did not find that peak vertical ground reaction force variability was related to speed. To our knowledge, no previous studies using normalized measures of variability have looked at peak variability of ap or ml GRF. These two measures followed previously found trends for spatiotemporal and gait related variables (Jordan et al., 2006; Jordan et al., 2007; Jordan et al., 2009). Our finding that the variability of peak vGRF did not relate to speed is not in agreement with the finding of Jordan et al. (2007) that it decreased as speed increased. We are not able to explain this occurrence, but can conject that it could possibly be due to a difference in subjects. The participants in this study were all male and consisted of mostly trained runners. Although not evaluated, we suspect that a large portion of our runners were not heel strikers. Jordan et al. (2007) tested only female subjects that were not as well trained as our subjects running a minimum of 15 MPW which were said to heel strike upon ground contact. Perhaps either differences in sex or foot strike impacts the relationship between variability of peak vGRF and speed.

Ground Reaction Force Variability and Training

The relationship between the variability of all three components of peak ground reaction force and training reached significance. Though the EXP group had less variability than the NON group, the EXP and REC groups were not different from one another. Group differences in the variability of ground reaction forces were expected to be different between all groups as the effect of training was thought to warrant continued changed in variability as found by Nakayama et al. (2010) for stride interval variability between trained runners and non-runners and by Chapman et al. (2008) for EMG variability of the shank muscles between highly trained runners and lesser-trained runners.

The lack of a finding in difference between the EXP and REC groups for ground reaction force variability in this study could signify a diminishing training inducted adaptation with increased train volume that is reflective of variability. This would mean that much of the adaptation resulting in decreased variability occurs prior to reaching a consistent volume of 20MPW.

Electromyography Variability and Speed

We found a significant relationship between the variability of Gn activation and speed during Br, where variability decreased as speed increased. This finding was in agreement with our own findings for ap and ml GRF as well as previous findings for gait cycle related variables (Jordan et al., 2006; Jordan et al., 2007; Jordan et al., 2009). It is proposed that this relationship reached significance during the Br phase since the others have shown that the Gn is one of the most active muscles during this phase (Gazendam & Hof, 2007).

No significant relationships were found between the variability of TA activation and speed for PA, Br, or Pr phases. The failure of the speed and variability of TA activation relationship to reach significance could be to the lack of a role that the muscle plays over the PA, Br, and Pr phases. The TA muscle has been shown to be most involved during the swing phase (Gazendam & Hof, 2007) which we did not evaluate.

Perhaps the most interesting finding in this study is that the Speed × Phase interaction effect found for the RF appeared to exhibit a positive relationship between speed and variability during the PA phase for all groups, defying previously found trends for other non EMG variables (Jordan et al., 2006; Jordan et al., 2007; Jordan et al., 2009) as well as our own findings for other running related variables. We believe that this could be related to the role of that the RF plays in allowing an individual to reach higher speeds, as it tends to be increasingly more active with earlier onset of activity with speed (Gazendam & Hof, 2007). The findings of Gazendam & Hof (2007) suggested that speed increase in running is mainly accomplished by a larger leg swing due to increased hip flexor and extensor action which includes the RF muscle. This again highlights the complex nature of

EMG variability during running. Perhaps the increased activity of the RF with speed during the swing phase (Gazendam & Hof, 2007) coincides with greater variability of the muscle, allowing an individual to meet the constraints of higher speeds.

Unlike the Gn and RF muscles, we did not find a relationship between variability of BF activation and speed for PA, Br, or Pr. It should be noted, however, that a Speed × Phase effect for Br was trending toward significance ($p = 0.16$). Given the limited sample size of the study, it is possible that there is still a relationship between the BF and speed.

Electromyography Variability and Training

The relationship between variability of activation and training experience did not reach significance for the Gn, TA, or RF. These results for the TA and Gn were not in agreement with Chapman et al. (2008) who found that highly trained runners had less TA, Soleus, and lateral gastrocnemius activation than lesser-trained runners. While it is unlikely, the reason for the lack of significance for the Gn could be attributed to that we used the medial gastrocnemius while Chapman et al. (2008) used the lateral gastrocnemius. We do not have any other explanation for this occurrence.

Regarding the TA, we believe that this disagreement with Chapman et al. (2008) could be due to the TA being more involved during swing phase and PA than it is during stance where it fires little (Gazendam & Hof, 2007). This study did not evaluate the variability of EMG during the entire swing phase and instead only did for the PA (50ms prior to contact) and braking and propulsive phases, whereas Chapman et al. (2008) evaluated the variability of EMG of the TA muscle for the entire gait cycle (including swing phase). In support of this, a main effect of phase was found which revealed that PA had a higher CV value than Br but not Pr, and Br and Pr were not different from one another.

Unlike the other muscles, a relationship was found between training experience and variability of BF activation during PA where greater experience meant less variability (EXP<REC<NON). This was also in agreement with previous findings that greater running experience results in decreased CV (Nakayama et al., 2010; Chapman et al., 2008). Aside from the

BF during PA (EXP had lower CV than REC, $p = 0.05$), this study did not find statistically significant differences in variability between the Experienced and Recreational groups for any other variables. Though this is not consistent with the findings of Chapman et al. (2008), it is proposed that a stricter cutoff of minimum MPW run for the REC group was likely the cause. This study intentionally chose a >20 MPW requirement to lessen the disparity between the REC and EXP groups so that a more evenly distributed representation of the training continuum was represented. The lack of significance difference between these two running groups suggests that much of the adaptation resulting in decreased variability occurs prior to reaching a consistent volume of 20MPW. Future studies could look at even more ranges of MPW along the training continuum between non-runners, moderately-trained runners, and experienced runners to identify the nature of this long-term relationship between specialized running training and variability. Given that we found less disparity between EXP and REC groups than Chapman et al. (2008), it is hypothesized that there is a threshold at which an increase in volume of specialized training does not result in a decrease in variability.

Limitations

While previous studies looked at variability in gait cycle measures during running have used the method of determining experimental running speeds as a percentage of preferred running speed (PRS), this study elected to used set speeds, beginning with 2.5 m/s and increasing in increments of 0.5 m/s to a minimum final speed of 4.5 m/s. This standardization of speeds allowed for all subjects to be compared over the same range of speeds, which eliminated the possibility that between groups differences in variability could be attributed to differences in PRS. Admittedly, one possible drawback of the standardization of speeds in this study is that it likely decreases the likelihood of finding potential PRS dependent non-linear U-shaped relationships between variability and speed and/or group, such as those that have been found with long ranged correlations (Jordan et al., 2006; Jordan et al., 2009).

Unlike a number of previous studies that have used time normalization techniques of EMG data for the comparison of individuals and groups (Chapman et al., 2008), this study elected not to. Instead, it defined gait phases (PA, Br, Pr) for each of the 10 selected strides and then calculated average values for the variables of interest across those 10 strides. It was thought that this method would better represent EMG data during specific phases (PA, Br, Pr) as EMG profiles are known to be highly variable between individuals (Guidetti, Rivellini, & Figura, 1996) and the timing of gait phases and EMG profiles are speed dependent (van Hedel et al., 2006).

Whereas previous studies have used long ranged correlations such as the DFA exponent (which require extended running periods) to investigate variability in locomotion (Jordan et al., 2006; Jordan et al., 2009; Nakayama et al., 2010) this study was unable to do so. The highly competitive professional and collegiate athletes within our subject pool had very strict training protocols, with which the investigator did not want to substantially interfere with. To ensure these athletes' participation, the running trials were limited to 30s per speed trial. Still, the researchers were provided with a rare opportunity to study the variability of locomotion related variables in a not often studied population; the members of the EXP group not only regularly engaged in high volume training but included some national class and professional runners.

Conclusion

As previously found for spatiotemporal parameters (Jordan et al., 2006; Jordan et al., 2007; Jordan et al., 2008) and vertical ground reaction forces (Jordan et al., 2007), we found that the variability of apGRF and mlGRF decrease with speed. We did not find any significant 3-way interaction effects of Group × GRF × Speed or Group × Phase × Speed, however the PA phase of the BF muscle did appear to be trending toward significance ($p = 0.155$). We also found few differences in variability between the EXP and REC group which could be an indicator that much of the variability related training adaption occurs prior to 20MPW of training volume. Unexpectedly, we found that the variability of the RF muscle during PA actually increased with speed. We speculate that this could be its increasingly greater activation during swing phase with speed. Our findings suggest that the interactions between EMG variability, speeds, and group may be more complex and require further investigation. Future work should further explore the speed dependency of EMG variability for different muscle groups as well as the impact that training has on the modulation of muscle activity across speeds.

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Vita

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