# THE EFFECTS OF VERTICAL JUMP AND SPRINT FATIGUE ON WHOLE-BODY BIOMECHANICS

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Original scientific paper
DOI: 10.26582/k.56.2.6

**Abstract:**

This study compared the kinetic and kinematic variables measured by a three-dimensional markerless motion capture system (MCS) to identify alterations in lower-extremity performance following vertical jump (VJ) and sprint anaerobic fatiguing tasks. Eleven females ($\bar{X}$±SD; 20.8±1.1 years, 72.2±7.4 cm, 68.0±7.2 kg) and eleven males (23.0±2.6 years., 180.3±4.8 cm, 80.4±7.3 kg) volunteered to participate in the present investigation. Participants were screened using the Functional Motion Analysis (FMA) protocol, consisting of 19 full-body motions, from which algorithm-derived scores were calculated [i.e., composite, power, functional strength, dysfunction, vulnerability, and exercise readiness score (ERS)] pre- and post-fatiguing tests. Each participant completed one familiarization session and three randomized acute fatiguing protocols [i.e., control, repeated vertical jump test (RVJT), 25-second resisted sprint test]. The repeated measures MANOVA indicated a statistically significant three-way interaction (score x condition x time). Follow-up analyses indicated differences between pre- and post-tests in composite score (1556.43±307.8; 1368.00±264.62), power score (813.34±242.39; 687.32±164.83), and ERS (18.16±4.75; 16.02±3.54) during the RVJT experimental sessions, respectively. The FMA scores suggested decrements in performance are first observed in the decreases in power production during high velocity movements (i.e., RVJTs), and the viability of a MCS to evaluate biomechanical alterations following fatiguing tasks.

***Key words:*** *kinetics, kinematics, markerless motion capture, performance*

## Introduction

Technology and motion capture systems (MCS) have experienced growth over the past few decades. These improvements have led to analytical tools that allow detailed analyses of the counter-movement vertical jump (CMVJ), and to determine the vertical displacement of the center of mass (COM) (Feltner, Bishop, & Perez, 2004; Feltner, Fraschetti, & Crisp, 1999; Hara, Shibayama, Takashita, Hay, and Fukashiro, 2008; Lees, Vanrenterghem, & Clercq, 2004). These devices have been used to assess an individual's upper- and lower-body motions, both explosive and functional in nature. Furthermore, a MCS allows derivation of the individual joint torques and ground reaction forces (GRF) produced. Markerless MCS quantifies the kinetic and kinematic movements of body segments and joints that influence the forces generated, and the enhancement of performance during a CMVJ with an arm swing (Fry, Herda, Sterczala, Cooper, & Andre, 2016; Mosier, Fry, & Lane, 2019; Perrott, Pizzari, Cook, & McClelland, 2017), or biomechanical alterations following anaerobic fatiguing tasks (i.e., vertical jump and resisted sprints) (Mosier, 2018). For example, Cabarkapa, Fry, and Mosier (2020) reported strong agreement in peak force and power for a basketball dunking motion between markerless MCS and a uni-axial force plate as a criterion measure. These advancements in MCS and screening protocols can be used to identify athletes at risk when performing various types of sport-specific movements. One published study by Mosier, Fry, Moodie, Moodie, and Nicoll, (2018) demonstrated the capability of a markerless MCS of identifying high-risk for non-contact season-ending injuries among American football athletes.

There are a wide variety of anaerobic tests that incorporate different modes of exercise or movement patterns, which also vary in duration, in order to test the anaerobic capacity of athletes. Repeated jumps and sprinting protocols are becoming more prevalent for assessing athletes' anaerobic power and capacity. The Bosco test is a popular test consisting of repeated jumps, in which an athlete performs continuous vertical jumps (VJ) for a specific duration (typically 60 sec) (Bosco, Luhtanen, & Komi, 1983; McNeal, Sands, & Stone, 2010). The jump test was reported to be suitable to evaluate the power output of leg extensor muscle during natural motion (Bosco, et al., 1983). Currently, the Wingate anaerobic test on a cycle ergometer is the most used and reported anaerobic performance test (Bar-Or, 1987; Inbar, Bar-Or, & Skinner, 1996; McLain, Wright, Camic, Kovacs, Hegge, and Brice, 2015). However, several sports that incorporate running may result in a more accurate anaerobic performance test assessment. McLain et al. (2015) indicated the non-motorized treadmill (NMT) (typically 25 sec with resistance of 18% of body weight) offers a suitable tool for the assessment of all-out sprint performance, thus providing an athlete with the ability to exert peak anaerobic power and measure anaerobic capacity.

Athletes often become fatigued during athletic events and anaerobic or aerobic performance assessments. With the onset of athletic fatigue, reaction times to external stimuli are delayed and injuries are more likely to occur (Chappell, et al., 2005). Fatigue is an intrinsic factor affecting the musculoskeletal and neurological systems (Benjaminse, et al., 2008; Chappell, et al., 2005). The system of fatigue can create an environment that increases the risk of non-contact injuries or more specifically anterior cruciate ligament (ACL) injuries by altering the lower extremity loading and landing strategies. ACL injuries are among the most common knee injuries observed in athletes (Agel, Olsen, Dick, Arendt, Marshall, & Sikka, 2007; Arendt, Agel, & Dick, 1999; Dick, Putukian, Agel, Evans, & Marshall, 2007; Mihata, Beutler, & Boden, 2006). Non-contact ACL injuries are common in team sports such as soccer, basketball, field hockey, and volleyball (Agel, et al., 2007; Arendt, et al., 1999; Dick, et al., 2007; Mihata, et al., 2006). As a result of the explosive and high fatiguing nature of these team sports, the muscular performance is notably impacted. The result of fatigue has been reported to decrease motor control performance (Johnston 3rd, Howard, Cawley, & Losse, 1998; Wojtys, Wylie, & Huston, 1996), increase knee joint laxity (Rozzi, Lephart, & Fu, 1999; Skinner, Wyatt, Stone, Hodgdon, & Barrack, 1986; Wojtys, et al., 1996), decrease balance skill (Johnston 3rd, et al., 1998), and decrease proprioception (Hiemstra, Lo, & Fowler, 2001; Lattanzio & Petrella, 1998; Lattanizio, Petrella, Sproule, & Fowler, 1997; Miura, et al., 2004; Rozzi, et al., 1999). With the onset of fatigue, the capacity of muscle fibers to absorb energy decrease and neuromuscular function alters, which has been shown to increase anterior tibial transition (Rozzi, Lephart, Gear, & Fu, 1999; Skinner, Wyatt, Hodgdon, Conard, & Barrack, 1986). These effects indicate a decreased capacity for controlling body movement and may indicate fatigue as a contributor to non-contact ACL injuries (Benjaminse, et al., 2008; Hiemstra, et al., 2001; Nyland, Shapiro, Caborn, Nitz, & Malone, 1997; Rodacki, Fowler, & Bennett, 2001). Chappell et al. (2005) suggested that vertical jump and sprint fatiguing protocols caused subjects to land with increased proximal tibia peak anterior shear force and decreased knee flexion at the time that peak anterior sheer force occurs (Pappas, Scheikhzadeh, Hagins, & Nordin, 2007). Similarly, muscle fatigue has been shown to alter the lower extremity biomechanics of healthy individuals (Nyland, et al., 1997; Pinniger, Steele, & Groeller, 2000). Madigan and Pidcoe (2003) assessed the effects of lower extremity muscle fatigue on drop-landing biomechanics and documented an increase in performance at the hip to compensate for the weakness created in the thigh muscles. Furthermore, Bishop et al. (2022) recently reported the usage of countermovement vertical jump for performance assessments, monitoring of neuromuscular fatigue, and a part of a test battery for return to performance among injured athletes. Further evaluation of the biomechanical changes during performances will give future insight into how fatigue can be rated and how to prevent fatigue-related injuries.

Therefore, the aim of the present study was to examine the acute whole-body biomechanical alterations following vertical jump and sprint anaerobic fatiguing tasks using functional motion analysis (FMA) screening scores. It was hypothesized that an innovative three-dimensional (3D) markerless MCS would detect and determine biomechanical alterations following fatiguing tasks. In addition, it was also hypothesized that both the VJ fatiguing and sprint fatiguing tasks would cause acute biomechanical alterations specifically to the lower-body extremities. Understanding acute whole-body biomechanical fatigue may further provide information for understanding when an athlete begins altering mechanics to sustain performance.

## Methods

### Study sample

Eleven healthy, recreationally active females ($\bar{X}$±SD); age=20.8±1.1 years, height=172.2±7.4 cm, body mass=68.0±7.2 kg), and eleven healthy, recreationally active males (age=23.0±2.6 years, height=180.3±4.8 cm, body mass=80.4±7.3 kg) volunteered to participate in the present investigation.

All participants were physically active for a minimum of one hour for three days a week for at least the preceding three months. None of the participants reported a history of current or prior neuromuscular diseases or musculoskeletal injuries specific to the ankle, knee, or hip joints. Participants demonstrated functional range of motion in hip, knee, ankle, and shoulder joints without limiting mechanical motion and performance during squats, VJ, and running tasks. This study was approved by the University's institutional review board for human subjects' research. Each subject read and signed an informed consent form and completed a health history questionnaire prior to participating.

### Study design

Each participant visited the laboratory four times: for one familiarization session, one control session, and two experimental sessions. The familiarization consisted of informed consents signing, VJ and sprint screening, a warm-up protocol, practice low intensity fatiguing protocols, and completion of the FMA. During the experimental session, participants completed a 10-min standardized warm-up protocol followed by performing the pre-test FMA, starting with the jump motions, followed by the squat motions, and then the remaining motions. The participants preformed one of the three randomized acute anaerobic fatiguing protocols [i.e., control session, repeated vertical jump test (RVJT), 25-second sprint test] followed by the post-test FMA (Figure 1). Each participant completed one session per week at the same time of day. The laboratory temperature (24-28°C) and humidity (38-42%) remained within a consistent range.

### Functional motion analysis (FMA)

The FMA is a collection of 19 different motions to assess an individual's upper extremity and lower extremity functioning using the 3D markerless MCS. The motions include shoulder ranges of motion (ROM) (i.e., shoulder abduction and adduction, shoulder horizontal abduction, shoulder internal and external rotation, shoulder flexion and extension), trunk rotation, bilateral overhead squat, right and left leg unilateral squat, right and left leg lunge, right and left leg 20-sec balance test, bilateral CMVJ, right and left unilateral CMVJ, concentric VJ, five right leg and five left leg VJs, and depth jump. All nineteen motions are incorporated into the FMA report. Cabarkapa, D., Cabarkapa, D.V., Philipp, Downey, and Fry (2022) recently examined the reliability of FMA scores and determined good to excellent reliability across multiple sessions (i.e., two sets of three FMA separated one week apart; six in total).

The motions that were believed to be most affected by the acute fatigue were tested first; thus, the jump motions first, followed by the squat motions, and the remaining motions. The order of the FMA during the experimental sessions was the following: bilateral CMVJ, right and left unilateral CMVJ, concentric VJ, five right leg and five left leg VJs, and depth jump, bilateral overhead squat, right and left leg unilateral squat, right and left leg lunge, right and left leg 20-sec balance test, shoulder abduction and adduction, shoulder horizontal abduction, shoulder internal and external rotation, shoulder flexion and extension, and trunk rotation.

### Functional motion analysis scores

The nineteen motions of the FMA were used to calculate six different performance scores focusing on certain movement variables. These scores were: the composite score, power score, strength score, dysfunction score, exercise readiness score, and vulnerability score. The composite score is a cumulative score based on the overall performance (power score + functional strength score – dysfunction score). The power score consists of data from jump heights and is an aggregate of all the jump performances. The functional strength score is the accumulation of squat depths and is an aggregate of all the squat performances. The dysfunction score consists of asymmetries (upper limb, lower limb, and trunk), knee valgus, lower limb kinetic chaining, and balance performances. The exercise readiness score (ERS) is a scale that depicts the level of training and readiness. The score consists of three factors: rebalance, development, and optimization. The rebalance phase is a range from removal of compensations towards biomechanical symmetry between the right and left upper and lower extremi-

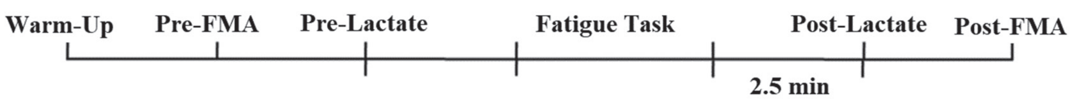


*Figure 1. The timeline that was conducted for the experimental sessions [repeated vertical jump test (RVJT), sprint, control].*

ties. All consisting of unilateral forces, joint flexions, and joint torques. The development phase is the evaluation of an individual's biomechanics towards kinetic and kinematic symmetry. The optimization phase is the maintenance of an individual's biomechanics and displaying peak performance mechanics. The vulnerability score is the aggregate of all performance, including stresses (consisting of unilateral high forces, joint flexions and joint torques), and compensation patterns (overuse of dominant side or limited usage due to history of an injury). This score is presented as a percentage of 0-100%. Cabarkapa, Caparkapa, et al. (2022) reported no statistically significant differences between algorithm based FMA scores from the markerless MCS indicating good to excellent reliability. Excellent reliability measurements were reported for readiness scores, good-to-excellent for functional strength and power scores, and moderate-to-excellent for dysfunction (Cabarkapa, Cabarkapa, et al., 2022), thus indicating the usage of the markerless MCS for the assessment of various types of biomechanical parameters.

## Acute fatigue protocols

*Warm-up protocol.* Each participant was instructed through a 10-min dynamic warm-up at the beginning of each experimental session. The warm-up consisted, in the order, of ten quadriceps pull to single leg Romanian deadlift reaches, ten tin soldiers, ten figure fours, ten walking lunges with a T-spine, five inchworms, forward skips with forward arm circles, backward skips with backward arm circles, forward skips with hip internal rotation, backward skips with hip external rotation, A-skips, A-skips to squat, and ten body-weight squats.

*Control session.* Each participant was instructed to sit for 15 min. The FMA was completed before the rest period in order of the jump motions, followed by squat motions, and remaining FMA motions. The FMA was completed by the blood samples taking, which were collected for lactate determination pre- and 2.5-min post-control period. Heart rate was collected with the chest strap (Polar FT1, Bethpage, NY, USA) throughout the entire session.

*Repeated vertical jump test.* During the repeated vertical jump test (RVJT), the participant was instructed to bend the knee to about 90 degrees and jump explosively, then repeat immediately on landing for one set (15 sec jumping, 15 sec rest, 15 sec jumping, 15 sec rest) lasting one minute in duration. Each participant completed five sets (5 min). The FMA was completed before the RVJT. This fatigue test was determined based on accumulated blood lactate responses during pilot investigation completed in our laboratory. Investigations during pilot testing comparing RVJT and Bosco 60-sec jump test resulted in greater blood lactate concentrations and post heart rate for RVJT. Heart rate was collected throughout the entire experimental sessions but was only reported pre- and post-test.

*25-second sprint test.* Each participant was attached to the resistive harness of a NMT (Woodway Force 3.0 treadmill, Waukesha, WI, USA), which was set to a resistance equal to 18% of the participant's body weight. Participants carried out a 25-sec maximal sprint on the Woodway NMT treadmill (McLain, et al., 2015). Heart rate was collected throughout the entire experimental sessions but was only reported pre- and post-test.

## Blood samples

Each participant gave three minimal blood samples (approximately one drop) at each testing session (baseline, pre, and post) by way of a lancet finger stick. Fingertip samples were collected into a lactate testing strip for analysis via a Lactate Plus handheld blood lactate analyzer (Nova Biomedical, Waltham, MA, USA). Baseline samples were collected following the warm-up protocol immediately prior to the pre-FMA. In addition, samples were collected before the randomized experimental and 2.5-min post experimental tests before the post-test FMA.

## Heart rate

Heart rate was collected with a chest monitor strap (Polar FT7, Polar Electro Inc., Bethpage, NY). Heart rate was collected throughout the entire experimental sessions; however, it was only reported pre-test and immediately post-test.

## Performance tests

*Motion capture device.* During each FMA motion performance, the kinetic and kinematic variables were collected and analyzed using the DARI (DARI Motion, Overland Park, KS, USA) 3D markerless MCS system. Anthropometric estimates (Winter, 1990) were used to estimate the segmental center of mass (COM)s. In addition, full-body GRFs and extremity joint kinematics were assessed. The 3D MCS has been shown to validly measure full-body and segmental kinetics and kinematics without a force plate or video, thus providing accurate performance measures (Fry, et al., 2016; Perrott, et al., 2017). In addition, MCS has been used to determine the contribution of the upper extremities during a CMVJ (Mosier, et al., 2019), and moderate-to-strong correlations were reported between FMA scores (i.e., readiness, functional strength, power) and traditional health-related physical fitness parameters such as estimated $VO_{2max}$ and body fat percentage (Cabarkapa, Whetstone, et al., 2022). Body fat percentage showed a weak positive correlation with vulnerability and moderate-to-strong positive correlation with ERS, power, and functional strength scores. $VO_{2max}$ showed a weak negative correlation with vulnerability and moderate-to-strong positive correlation with ERS, power, and functional strength scores, thus further indicating that MCS performance scores may be used as a non-invasive testing alternative or in conjunction with currently implemented traditional testing modalities (Cabarkapa, Whetstone, et al., 2022).

*Force plate device.* During each squat and jump motion, the kinetic variables were collected and analyzed using a uni-axial force plate (Rice Lake Weighing Systems, Rice Lake, WI, USA) through a data acquisition system (Biopac MP 150 System, Goleta, CA, USA) sampling at 1000 Hz to monitor the GRF. In addition, the RVJT was collected and analyzed to determine flight time and positive impulse with a sampling rate of 1000 Hz.

*Non-motorized treadmill.* During the 25-sec sprint test, the kinetic variables were collected on the NMT (Woodway Force 3.0 treadmill, Waukesha, WI, USA), which was set to a resistance equal to 18% of the participant's body weight (McLain, et al., 2015).

### Statistical analyses

Statistical analyses were conducted for the performance measures with a factorial repeated measures MANOVA using the FMA scores (composite score, power score, functional strength score, dysfunction score, exercise readiness score, and vulnerability score) x conditions (RVJT, sprint, CON) x time (pre-test, post-test) x sex (females, males). A Pearson correlation matrix was used to compare the relationship between each of the FMA scores during the familiarization session. Two separate 2-way repeated measures (RM) ANOVAs were used to examine the differences in HR [condition (RVJT, sprint, CON) x time (pre-test, post-test)] and in accumulated blood lactate [condition (RVJT, sprint, CON) x time (pre-test, 2.5-min post-test)]. Paired samples *t*-tests were used to examine the differences in flight times and positive impulses of the second jump of set one and last jump of set five during the RVJT. These VJs were selected to include the VJ rebound and the next CMVJ. *Post-hoc* comparisons were conducted when needed using the Bonferroni correction. The level of significance was set *a priori* at $p \leq .05$ for the statistical tests. Statistical analyses were performed using SPSS 24 (IBM Corporation, Amonk, New York, USA) and Microsoft Excel 2016 (Microsoft Corporation, Redmond, WA, USA).

## Results

Table 1 lists the descriptive statistics (mean and standard deviations ($\bar{X} \pm$ SD) and pre- and post-test significance levels for the FMA scores for each pre-test and post-test during each condition. The Pearson correlations matrix (Table 2) indicated moderate to strong correlations between the FMA scores, indicating the scores should be analyzed via a MANOVA (score x condition x time x sex). The MANOVA indicated a three-way interaction (score x condition x time) ($p=.01$). Follow-up analyses indicated significant differences between pre- and post-tests for the composite score ($p<.01$), power score ($p<.01$), and ERS ($p<.01$) during the RVJT experimental sessions.

Table 3 lists the HR during the pre- and post-tests, and accumulated blood lactate during the

*Table 1. Reporting Motion Capture System (MCS) composite, power, functional strength, dysfunction, vulnerability, and exercise readiness scores in the pre- and post-test during the repeated vertical jump (RVJT), spring, and control (CON) experimental sessions*

| Condition | Sex | MCS composite | Power score | Functional strength score | Dysfunction score | Vulnerability score | Exercise readiness score |
|---|---|---|---|---|---|---|---|
| Pre-RVJT | F | 1387.2 ± 184.6 | 665.6 ± 86.0 | 830.6 ± 97.4 | 108.8 ± 48.8 | 40.9 ± 10.1 | 16.0 ± 2.3 |
| | M | 1839.2 ± 159.4† | 1015.3 ± 132.0† | 949.7 ± 83.1† | 126.0 ± 32.3 | 37.0 ± 8.0 | 21.7 ± 2.3† |
| Post-RVJT | F | 1217.9 ± 166.9* | 585.5 ± 45.1 | 779.2 ± 113.0 | 146.7 ± 60.8 | 46.7 ± 11.0 | 13.8 ± 1.6* |
| | M | 1518.1 ± 264.1*† | 789.2 ± 173.6*† | 883.6 ± 101.8*† | 163.7 ± 73.5 | 42.6 ± 13.4 | 18.2 ± 3.6*† |
| Pre-sprint | F | 1414.8 ± 212.1 | 691.1 ± 95.4 | 840.5 ± 101.5 | 116.7 ± 37.1 | 39.9 ± 7.1 | 16.4 ± 2.2 |
| | M | 1804.0 ± 143.0† | 999.0 ± 126.1† | 928.3 ± 107.4 | 123.2 ± 56.6 | 37.6 ± 9.1 | 21.0 ± 2.3† |
| Post-sprint | F | 1365.9 ± 170.1 | 633.8 ± 82.2 | 838.6 ± 85.4 | 164.5 ± 203.2 | 41.6 ± 7.3 | 15.4 ± 1.9 |
| | M | 1662.8 ± 221.9† | 889.9 ± 155.2*† | 907.4 ± 114.8 | 131.6 ± 48.0 | 37.8 ± 10.9 | 20.2 ± 2.8† |
| Pre- CON | F | 1387.3 ± 210.1 | 655.3 ± 106.3 | 834.6 ± 85.4 | 102.6 ± 44.5 | 40.6 ± 9.0 | 15.7 ± 2.6 |
| | M | 1799.7 ± 145.6† | 965.1 ± 138.2† | 948.7 ± 100.4† | 114.2 ± 51.9 | 37.4 ± 10.2 | 21.3 ± 2.2† |
| Post-CON | F | 1354.7 ± 210.1 | 643.5 ± 121.1 | 823.9 ± 100.4 | 112.5 ± 46.7 | 41.1 ± 8.7 | 15.3 ± 2.9 |
| | M | 1676.4 ± 276.9† | 918.0 ± 160.2† | 806.1 ± 307.5 | 126.5 ± 51.3 | 39.0 ± 14.3 | 20.1 ± 3.5† |

Note. Mean ± SD for reported scores for females (F) and males (M). MANOVA indicates significant differences between score x condition x time ($p<.01$). * indicates significant differences between the pre- to post-FMA tests. † indicates significant differences between females and males ($p<.05$).

*Table 2. Pearson correlation matrix among the reported performance scores during the familiarization session*

| | Power score | Functional strength score | Dysfunction score | Vulnerability score | Exercise readiness score |
|---|---|---|---|---|---|
| MCS composite score | 0.90* | 0.78* | -0.41 | -0.26 | 0.92* |
| Power score | ---- | 0.47* | -0.12 | -0.18 | 0.89* |
| Functional strength score | ---- | ---- | -0.39 | -0.42 | 0.64* |
| Dysfunction score | ---- | ---- | ---- | 0.64* | -0.33 |
| Vulnerability score | ---- | ---- | ---- | ---- | -0.47* |
| Exercise readiness score | ---- | ---- | ---- | ---- | ---- |

Note. n=22; *correlation indicates significance (p<.05)

*Table 3. Heart rate and accumulated blood lactate changes during multiple time points throughout the repeated vertical jump test (RVJT), sprint, and control (CON) sessions*

| | | Heart rate (bpm) | | Accumulated lactate (mmol/L) | |
|---|---|---|---|---|---|
| Condition | Sex | Pre-test | Post-test | Pre-test | 2.5 min post-test |
| RVJT | F | 80.9 ± 15.5 | 183.9 ± 12.8*† | 2.6 ± 1.7 | 11.2 ± 2.4*† |
| | M | 69.9 ± 10.5 | 171.2 ± 23.9*† | 2.1 ± 1.2 | 13.6 ± 1.8*† |
| Sprint | F | 79.3 ± 18.9 | 168.5 ± 30.8*† | 2.5 ± 1.6 | 10.7 ± 2.0*† |
| | M | 75.1 ± 10.0 | 176.6 ± 8.8*† | 3.3 ± 3.0 | 14.8 ± 3.0*† |
| CON | F | 75.4 ± 18.9 | 74.7 ± 6.4 | 1.7 ± 0.5 | 3.1 ± 2.9 |
| | M | 81.6 ± 17.0 | 86.7 ± 11.9 | 3.2 ± 2.5 | 2.3 ± 2.2 |

Note. Heart rate and change in accumulated blood lactate for females (F) and males (M). * indicates significant differences between the pre- to post-test, † indicates significant differences from the control (p<.05).

*Table 4. Vertical jump performances $\bar{X} \pm SD$ for females (F) and males (M) during the repeated vertical jump test (RVJT) during the first and jumping last set*

| | Set 1 | | | Set 5 | | | | |
|---|---|---|---|---|---|---|---|---|
| | Jump 2 of Set 1 | | | Last jump of Set 5 | | | | |
| Sex | # of jumps | Flight time (ms) | Positive impulse (N·sec) | # of jumps | Flight time (ms) | Positive impulse (N·sec) | Change in flight time (%) | Change in positive impulse (%) |
| F | 13.0 ± 1.0 | 0.4 ± 0.1 | 250.0 ± 48.5 | 13.0 ± 1.0 | 0.3 ± 0.0* | 161.5 ± 52.8* | -33.7 ± 12.7 | -33.8 ± 20.4 |
| M | 14.0 ± 1.0 | 0.5 ± 0.0 | 381.4 ± 46.5 | 13.0 ± 1.0 | 0.3 ± 0.1* | 204.1 ± 80.5* | -41.8 ± 9.7 | -46.2 ± 20.6 |

Note. Females (F), Males (M). * indicates significant differences between set 1 and set 5, (p<.05). Change in flight time and positive impulse during the selected vertical jump.

*Table 5. Sprint performance $\bar{X} \pm SD$ of females (F) and males (M) during the 25-sec non-motorized resisted sprint test*

| Sex | Distance (m) | Mean sum force (N) | Mean power (W) | Peak power (W) | Change in power (%) | Mean velocity (m/s) | Peak velocity (m/s) | Change in velocity (%) |
|---|---|---|---|---|---|---|---|---|
| F | 70.2 ± 7.5 | 155.4 ± 15.9 | 400.4 ± 76.2 | 1577.1 ± 316.4 | -47.4 ± 12.2 | 2.8 ± 0.3 | 3.5 ± 0.5 | -24.3 ± 6.8 |
| M | 94.7 ± 8.0 | 190.2 ± 17.1 | 716.3 ± 114.7 | 2825.2 ± 439.9 | -66.2 ± 11.0 | 3.8 ± 0.3 | 5.1 ± 0.6 | -33.9 ± 10.8 |

Note. Mean sum force is the sum of horizontal and vertical forces; mean power and mean velocity is the average across the 25-sec sprint; peak power and peak velocity is the maximum value across the 25-sec sprint; change in power and change in velocity is the difference between the maximum peak to the last foot stride peak represented as a percent.

pre-test and 2.5-min post-tests. A 2-way ANOVA indicated a significant interaction for HR (condition x time) (p<.01). Follow-up analysis indicated the post-test HR was significantly greater than pre-tests (p<.01). Furthermore, the RVJT (p<.01) and sprint (p<.01) conditions were significantly greater compared to the CON during the post-tests. In addition, a 2-way RM ANOVA indicated a significant interaction for accumulated blood lactate (condition x time) (p<.01) (Table 3). Follow-up analysis indicated post-test lactate accumulation was significantly greater compared to the pre-tests (p<.01), and the RVJT and sprint conditions were significantly greater than the CON (p<.01).

Table 4 lists the number of jumps, flight time, and positive impulse of set one and set five during the RVJT. The paired samples *t*-tests indicated the flight time (p<.01) and positive impulse (p<.01) during the last vertical jump during set five were significantly less than the second jump of set one for both males and females (Table 4). Table 5 lists the force, velocity, and power during the 25-sec NMT treadmill sprint tests. The reduction in the FMA performance scores (pre-test vs. post-test) indicated females and males exhibited a reduction in power and velocity following the sprint test. Table 6 lists the fatigue rates for each FMA score per condition. The fatigue scores indicated the greatest reduction in the composite score, power score, and ERS, during the RVJT session.

## Discussion and conclusion

The notion that fatigue is a predisposing factor responsible for the increased number of musculoskeletal injuries is common in sports indicating the importance of pre-exercise screening and onset of fatigue screening in athletes. The current investigation determined that an innovative 3D MCS was capable of detecting acute lower-body biomechanical changes due to acute fatigue. The MANOVA indicated a three-way interaction (score x condition x time) (p=.01). Further analysis of the FMA scores indicated alterations of performance occurred following the RVJT. The significant decrease in the power score can account for the reduction in the composite score due to the calculation of the composite score (composite score = power score + functional strength score – dysfunction score). In addition, the power score is an aggregate of the VJ measurements. As a result, the bilateral CMVJ VJH decreased five centimeters from pre- to post-RVJT [pre-RVJT (48.5±15.0 cm), post-RVJT (43.2±9.4 cm)]. Further examination can account for reduction in the power score due to the decrease in the power and velocity, as a result of the onset of fatigue following the RVJT. This decrease in power and velocity can further be explained by the reduction in VJH. Although significant changes were not observed for the functional strength scores, this can be explained by the measurements of the score which is an aggregate of all squat and lower-limb motions. Although there was an onset of muscle fatigue, the squat motion mechanics were not affected by the fatiguing tasks. The differences in the power and functional strength scores further indicate that high power and velocity movements are the first to falter and are most susceptible to fatigue. Fry et al. (1994) has indicated that strength is maintained unless the fatigue stimulus is extended for a longer duration. The significant decrease in the ERS following the RVJT indicates a change in one of the three categories (rebalance, develop, optimization) used in determining ERS. It is speculated the decrease in ERS is a result of the decrease in the optimization score due to the acute decrease in the velocity and power performance. The optimization score is the performance phase in which individuals can display the foundation of simple and complex mechanics by providing maintenance of biomechanics and displaying peak performance.

There were no changes in either the vulnerability score or the dysfunction score further suggesting that these measures are more stable scores. Furthermore, the acute RVJT fatigue did not significantly affect the asymmetry, kinetic chaining, compensation, or balance performances. The 4-way MANOVA did not report an interaction for sex. Further examination indicated that, although the performance scores varied between sex, males and females responded in a similar manner from pre- to post-tests.

The FMA fatigue rates (comparison of pre-test versus post-test mean scores) indicate the greatest reduction in performance among the FMA scores from pre- to post-test for each condition (Table 6). The greatest decrease in performance was indicated by the composite score, power score, and ERS. Furthermore, the greatest decrease in FMA scores were observed during the RVJT. No changes were

*Table 6. Reported the fatigue rates $\bar{X} \pm SD$ for the MCS composite, power, functional strength, dysfunction, vulnerability, and exercise readiness scores during the repeated vertical jump (RVJT), sprint, and control (CON) experimental session*

| Condition | Sex | MCS composite score | Power score | Functional strength score | Dysfunction score | Vulnerability score | Exercise readiness score |
|---|---|---|---|---|---|---|---|
| RVJT | F | -11.9 ± 8.1 | -11.40± 9.2 | -6.2 ± 8.3 | 57.9 ± 96.7 | 17.2 ± 23.4 | -12.6 ± 8.9 |
| | M | -17.7 ± 10.1 | -22.7 ± 11.1 | -7.0 ± 5.6 | 46.0 ± 94.4 | 21.4 ± 47.4 | -16.2 ± 11.8 |
| Sprint | F | -3.0 ± 5.2 | -8.0 ± 7.2 | -0.1 ± 6.8 | 48.7 ± 170.4 | 5.3 ± 18.3 | -6.0 ± 6.3 |
| | M | -7.7 ± 10.9 | -10.6 ± 13.5 | -1.9 ± 9.6 | 20.7 ± 52.0 | 2.7 ± 23.9 | -3.6 ± 12.6 |
| CON | F | - 2.3 ± 10.0 | -1.0 ± 17.7 | -1.3 ± 5.5 | 26.6 ± 80.5 | 4.0 ± 23.4 | -2.1 ± 13.5 |
| | M | -7.1 ± 11.3 | -5.2 ± 3.9 | -15.1 ± 31.6 | 25.4 ± 62.7 | 3.6 ± 15.5 | -6.1 ± 10.0 |

Note. Fatigue rate is the difference between the pre- and post-score as a percent of mean change across participants.

observed in the dysfunction score and vulnerability score, further indicating these are stable scores as previously stated (Cabarkapa, Cabarkapa, et al., 2022).

The significant increases in accumulated lactate from pre- to 2.5-min post-test indicate that the RVJT and resisted sprint tests involved anaerobic glycolytic fatigue. In addition, both acute fatiguing tasks were significantly different from the CON session. Similar accumulated lactate responses for pre- to post-tests were observed for both fatiguing sessions. Previous research has indicated blood lactate reaching 15.4 mmol/L following a Wingate test and 8.1 mmol/L following the Bosco 60-sec jump test (Bosco, et al., 1983). Both measurements were collected 5-min post-fatigue exercise. In comparison, the RVJT post-test accumulated of 12.4 mmol/L 2.5 minutes post-test indicated the task was more anaerobically demanding than what was previously reported for the Bosco 60-sec jump test due to the duration and production of work during the fatiguing task. McLain et al. (2015) reported accumulated lactate of 15.8 mmol/L 5 minutes following the 25-sec resistance sprint. The current investigation reported accumulated lactate of 14.5 mmol/L 2.5 minutes post-test. The measurement of accumulated lactate levels 2.5-min post-fatigue test was done to prevent excessive recovery from affecting the biomechanical assessment during the post-FMA test. The time in which the blood lactate concentration was drawn post-fatigue test occurred before the peak blood lactate concentration (5 min) and the duration reported (Weltman, 1995). Blood lactate concentration collection at 2.5-min post only prevented the collection of the peak blood lactate concentration which would be observed at 5 minutes post exercise (Weltman, 1995). Furthermore, accumulated blood lactate indicated that these fatigue tests still indicated similar anaerobic fatigue responses and also suggested that these fatigue tests were performed with maximal effort. Maximal HR has not been reported by the Bosco jump test, RVJT, or the resisted sprint test. It is speculated HR will reflect elevation trends similar to the elevations in the accumulated blood lactate.

Similar decreases were observed in performance comparing the flight times and the positive impulse during the repeated jump test. Previous literature has reported that both a longer flight time or great positive impulse have indicated a higher VJH (Moir, 2008). Both the flight time and the positive impulse of the 2$^{nd}$ VJ of set one to the last VJ indicated a significant decrease in performance during the RVJT. Equal numbers of VJs per set were performed by both males and females. Therefore, individuals spent more time on the ground than in the air as participants fatigued, furthermore, performing the vertical jump of poor quality. Previous literature has reported similar decreases in velocity and power during the 25-sec sprint test (McLain, et al., 2015). A greater fatigue rate/index (% change) was indicated for the repeated jump test (i.e., flight times, positive impulses) and for the 25-sec resisted sprint test (power, velocity).

The maximal efforts exerted during the acute fatiguing tasks and the decrease in the FMA performance indicated that both the males and females presented an acute biomechanical fatigue. With the onset of athletic fatigue, reaction times to external stimuli are delayed and injuries are more likely to occur (Chappell, et al., 2005). Fatigue increases the risk of non-contact injuries by altering the lower extremity takeoff and landing strategies. Daggett, Witte, Cabarkapa, and Fry (2022) conducted markerless MCS assessments throughout an ACL reconstruction rehabilitation protocol. The MCS provided gradual improvements in functional strength and ERS throughout the 3-6 months post ACL reconstruction period (Daggett, et al., 2022), further emphasizing the importance of the individual-based assessment of return-to-play criteria.

As previously noted, athletes often become fatigued during athletic events and anaerobic or aerobic performances or training, thus, further increasing the probability of non-contact injuries. This risk of fatigue-related injury could potentially vary from a minor injury to a severe injury (i.e., season ending injury). Such injuries are more common in reactive team sports. As a result of the explosive and high fatiguing nature of these team sports, the muscular performance is notably impacted further impacting athletes' performance and success during a season. Depending on the likelihood of an injury and its severity, this would be affecting an athlete's performance, training, playing time, etc. In some cases, a higher seriousness of an injury may result in a season/career ending. Regardless of the significance of the injury, there is always a concern for the recovery rate and duration of recovery. Nonetheless, recognizing athletes' mechanical alterations in performance, which may occur either following acute bouts of fatigue or due to the longevity of a season, may provide further insight into injury prevention. It also provides an enhanced understanding of an athlete's success and durability during a season. Further evaluation of the biomechanical changes during performances will give future insight into how fatigue can be rated, which knowledge may contribute to injury prevention.

Biomechanical changes in motion performance are believed to decrease shock absorption and knee stabilization during landing. The human body is efficient at absorbing the shock of the GRFs during takeoff and landing of VJs. However, if the musculature surrounding the joints are not properly developed, maintained, or if they are fatigued, it may lead to ligament susceptibility and a chronic limitation (Brazen, Todd, Ambegaonkar, Wunderlich, & Peterson, 2010). This presents a limitation of the present investigation and provides one of the directions for future research (e.g., further examination of biomechanical alterations during sport-specific fatigue or chronic overreaching). Furthermore, evaluation of acute biomechanical fatigue rates may determine when an athlete is able to return to sport following rehabilitation or developed fatigue biomechanical alterations.

The current investigation may pose a few limitations due to the population sample size and the scope of the population in the current investigation. However, a statistical power test was calculated prior to the investigation resulting in an equal number of males and females who meet the qualifications. The current experimental research is of a randomized cross-over design, meaning that all participants completed all conditions in a randomized order. Further follow-up investigations are needed to examine larger samples sizes and different sample populations that would provide further insight into biomechanical alterations based on training status and competitive level.

In conclusion, the current findings of the present study demonstrated the viability of the MCS test to evaluate biomechanical alterations in performance due to the acute fatigue among recreationally trained males and females. Differences in FMA scores and performances following acute fatigue protocols indicated acute biomechanical alterations in the lower extremities, specifically following the RVJT. Similar fatigue indexes and physiological responses were reported for the RVJT and the 25-sec NMT sprint test. The pre- to post-test FMA scores indicated decrements in performance were first observed in the decreases in power production during high velocity movements (i.e., VJs), further indicated by the reduction in the pre-test to post-test vertical jump height (VJH). Further research is needed to examine the responses of different levels of athletes, responses to other fatiguing methods of different intensities and durations, acute and chronic fatigue such as during athletic seasons, and influences of fatigue on athletic performance. Further evaluation and understanding of biomechanical alterations during performance will provide future insight into how fatigue can be rated, thus contributing to fatigue-related injuries prevention. Non-invasive examination of athletic movements and biomechanical alterations following acute fatiguing protocols can be used to reduce injury risk. Further advancements in MCS technology and screening protocols may be capable of predicting increased risk of season-ending injuries.

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Submitted: January 3, 2024
Accepted: January 10, 2024
Published Online First: December 10, 2024

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