The Feasibility of Accelerometer-Derived Measures of Vertical Jump Height as a Marker of Neuromuscular Performance in Collegiate Soccer Players.

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Science
In
Human, Nutrition, Food, and Exercise

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May 10th, 2022
Blacksburg, VA

Keywords: countermovement jump, fatigue, soccer, reliability, applicability, accelerometer

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In female college soccer players, there is no protocol for assessing fatigue. A total of 40 members of the Virginia Tech Women's Soccer team participated in the countermovement jump assessment to find a reliable way to gauge player fatigue and readiness in these athletes. These were tested by assessing the within and between-day similarity of a countermovement jump test as a measure of neuromuscular performance by comparing multiple jump heights during jumps performed within a single day and on separate days. Additionally, to determine the responsiveness of countermovement jump height as a marker of fatigue, we compared jump heights before and after activities thought to induce fatigue and competitive matches. All subjects wore a STATSports APEX unit that includes an 18Hz GPS, 952 Hz accelerometer, and 952 Hz gyroscope situated on the upper back over the second thoracic vertebra using a manufacturer-provided vest. After each training session or match, the data was downloaded using the manufacturer's software (APEXA). A custom MATLAB program was then used to calculate CMJ height from vertical acceleration. Results showed that CMJ heights were very reliable both within and between testing days. CMJ heights were found to accurately decrease following both high-load training sessions and a competitive soccer match. For both activities, the decrease in performance was dependent on the amount of load experienced. Lastly, CMJ height did not recover the day following high training load sessions. Across a training week, CMJ consistently decreased each day. This was followed by a recovery in performance following two off days. The results suggest that the use of a trunk-mounted, GPS-embedded accelerometer and a novel three-jump protocol is responsive to assess CMJ height. In addition, it is responsive to estimating fatigue following soccer activity.

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In female college soccer players, there is no protocol for assessing fatigue. A total of 40 members of the Virginia Tech Women's Soccer team participated in the countermovement jump assessment to find a reliable way to gauge player fatigue and readiness in these athletes. We hypothesized that countermovement jump heights would not vary between jumps executed on the same day and on different days. We also hypothesized pre-training countermovement jump heights would vary across a 7-day training session with reductions dependent on the prior days' physical demands and would be reduced following a competitive soccer match, also dependent on each player's physical demands. These were tested by assessing the within and between-day reliability of a vertical jump test as a measure of performance by comparing multiple countermovement jump heights during jumps performed within a single day and comparing jumps on separate days. Additionally, to determine the feasibility of countermovement jump height as a marker of fatigue, we compared jump heights before and after activities thought to induce fatigue and competitive matches. All subjects wore a STATSports APEX unit that includes an 18Hz GPS, 952 Hz accelerometer, and 952 Hz gyroscope situated on the upper back over the second thoracic vertebra using a manufacturer-provided vest. After each training session or match, the data was downloaded using the manufacturer's software (APEX) and a custom MATLAB program was then used to calculate CMJ height from vertical acceleration. Results showed that CMJ heights were very reliable both within and between testing days. CMJ heights were found to decrease following both high-load training sessions and following a competitive soccer match. For both activities, the decrease in performance was dependent on the amount of load experienced. Lastly, CMJ height did not recover the day following a high training load sessions. Across a training week, CMJ consistently decreased each day. This was followed by a recovery in performance following two off days. The results suggest that the use of a trunk-mounted, GPS-embedded accelerometer and a novel three-jump protocol is reliable to assess CMJ height. In addition, it is feasible to estimating fatigue following soccer activity.

DEDICATION

This work is dedicated to my husband and my son – Casey Hines and Meyer Hines. Also, to those that have supported me in my professional and personal life in pursuit of this achievement.

ACKNOWLEDGMENTS

I would like to thank the following people:

Dr. Jay H. Williams for the opportunity to complete my graduate degree and guidance in the thesis process. I would not have been able to accomplish this without you.

My committee members Dr. David Tegarden, Dr. Valisa Hedrick, and Dr. Angela Anderson for the advice in the thesis process.

David Christian for sharing an office space with me and being a confidant.

The Virginia Tech Women's Soccer team for their time, commitment, and effort in performing to the best of their abilities.

My allies at Virginia Tech, from both undergraduate and graduate school, for helping me stay motivated, believe in myself, and attain this considerable achievement.

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INTRODUCTION

There is a multitude of ways to measure fatigue in athletes. Research has shown it can be anywhere from physiological to psychological markers that vary depending on the sport or even the person.[2] To begin to understand fatigue, literature has been attempting to narrow in on how to measure it. Physiological markers like heart rate, blood glucose, and vertical jump are some of the less difficult ways to quantify fatigue when trying to ensure readiness.[3] This in turn will help to prevent injury to individuals, specifically athletes. While the research supports this type of monitoring, its feasibility comes into question as it can be difficult to perform these measurements daily and in team sports composed of 30 or more players. It is necessary to review the literature and test whether vertical jump specifically is a reliable way to measure performance and can be applied in a field setting. This proposal includes a literature review justifying a need to routinely measure a player's "readiness" using a performance metric affected by fatigue. It will discuss the energy cost of soccer, vertical jumps as a measure of fatigue, vertical jumps and different training methods, and the reliability of accelerometers. More importantly, it will form the justification for using vertical jump performance as a fatigue and readiness metric.

Specific Aims

The overall goals of this research are to determine if countermovement jump is a reliable method to gauge player performance and can be reliably applied to a team of female soccer athletes. The specific aims are:

Specific Aim 1: To assess the within and between-day reliability of a vertical jump test as a measure of performance. This was accomplished by comparing multiple vertical jump heights during jumps performed within a single day. In addition, vertical jump heights were compared during jumps performed on separate days.

Specific Aim 2: To determine the feasibility of vertical jump height as a marker of performance. This was done by comparing jump heights before and after activities thought to induce fatigue. Specifically, the acute and long-term effects of seven days of training on vertical jump height were assessed. Also, the acute effects of competitive matches on vertical jump height were determined.

Hypotheses

1. Vertical jump heights will not be significantly different between jumps executed on the same day.
2. Vertical jump heights will not be significantly different between jumps performed on different days.
3. A soccer training session will result in a significant acute reduction in vertical jump height.
4. Pre-training vertical jump heights will be significantly correlated with load experienced across a 7-day training session.
5. Vertical jump height will be significantly reduced following a competitive soccer match as compared to pre-match jump height. Reductions will be dependent on the minutes played and workload performed.
6. Vertical jump height will be significantly reduced following a competitive soccer match for players experiencing high loads as compared to players experiencing low loads

Delimitations

This study is delimited to:

- Female Division 1 soccer athletes.
- The countermovement vertical jump protocol developed in this study.
- Use of the STATSports APEX accelerometer worn by each athlete.

Limitations

This study is limited by:

- The subject's sleep, diet, and external stressors (academics, social life, etc) were not measured nor controlled for.
- Extra physical activities subjects might have engaged in were not measured nor controlled for.
- Short between-jump time intervals may not have allowed athletes to adequately prepare for the subsequent jump.
- Motivation could have affected the jump height.
- A detailed analysis of acceleration and deceleration during each jump was not performed.

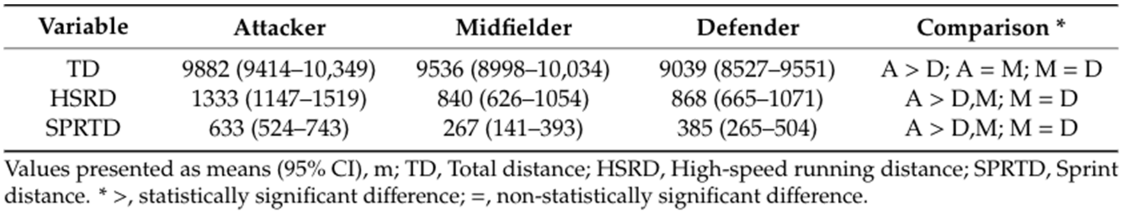
LITERATURE REVIEW

Introduction

Soccer is known to be a very demanding sport. Between intense training sessions, strength conditioning, and matches that can be once or twice a week during peak season, these athletes can fatigue quickly and put themselves at risk of injury. In order to prevent injury, laboratory measures of vertical jump performance have become a common way of gauging performance and fatigue levels.[4] To collect these measurements, the literature often mentions the use of a force plate in a laboratory setting and the increasingly common accelerometer.[5] Unfortunately, the daily use of a force platform with a large team of 30 players is impractical. An accelerometer or inertial measurement unit (IMU) that can be worn by participants may be a preferred choice as it can be used out in the field rather than simulating soccer-based activity in the laboratory. These have been known to accurately gauge fatigue levels in field situations using vertical jumps[6]; however, the face validity of accelerometers for data collection needs to be determined, as there is not much research supporting this claim. The aim of this review is to determine the usefulness of vertical jump and the useability of accelerometers as tools to gauge fatigue levels.

Energy Cost of Soccer

Soccer is considered a demanding sport due to rigorous training sessions, the variety of movements that are necessary during matches, and how often they are played. Matches can occur anywhere from once or twice a week, lasting 90 minutes with a 15-minute break in between and have the possibility of going into extra time (ET) to determine a winner if tied. It can also range greatly with a team sport whose training load can depend on the position and duration of play. For instance, soccer athletes can sometimes play for only 20 minutes in one match and the full 90 minutes in another. Trying to determine the most reliable and straightforward way to monitor fatigue levels in these athletes can help prevent injury. While considering these facts, there is not a sufficient amount of research examining the effects of soccer-specific exercise on elite female athletes, countermovement jump (CMJ) performance, or even fatigue. For the purpose of this review, CMJ is characterized by the participant starting in a standing position with their hands on their hips, squatting down, and then extending up. Alternatively, a squat jump (SJ) uses the same positioning and movements; however, he/she is asked to pause at the bottom of the jump before extending upwards. Athletes are expected to train in a way that will prepare them for these games where they will likely cover a distance of roughly 6.5 miles of sprinting at different speeds and intense maneuvering.[7] The physical demands and distance covered can also vary depending on the position being played. One study looked at the matches over four consecutive seasons for twenty-three female college Division 1 soccer athletes, all in different position groups. Matches were only included if the players participated in the match for the full 90 minutes without any substitution and positions were grouped by attacker, midfielder, and defender. Sausaman et al. found that there was no statistical difference when observing the total distance covered between position groups; however, there was a significant difference for attackers as they completed more high-speed running compared to other groups.[8] Table 1 below shows these results, depicting the significant difference in distance between attackers and both midfielders and defenders. In particular, it is shown that attackers have a significantly higher amount of high-speed running and sprint distance comparatively.

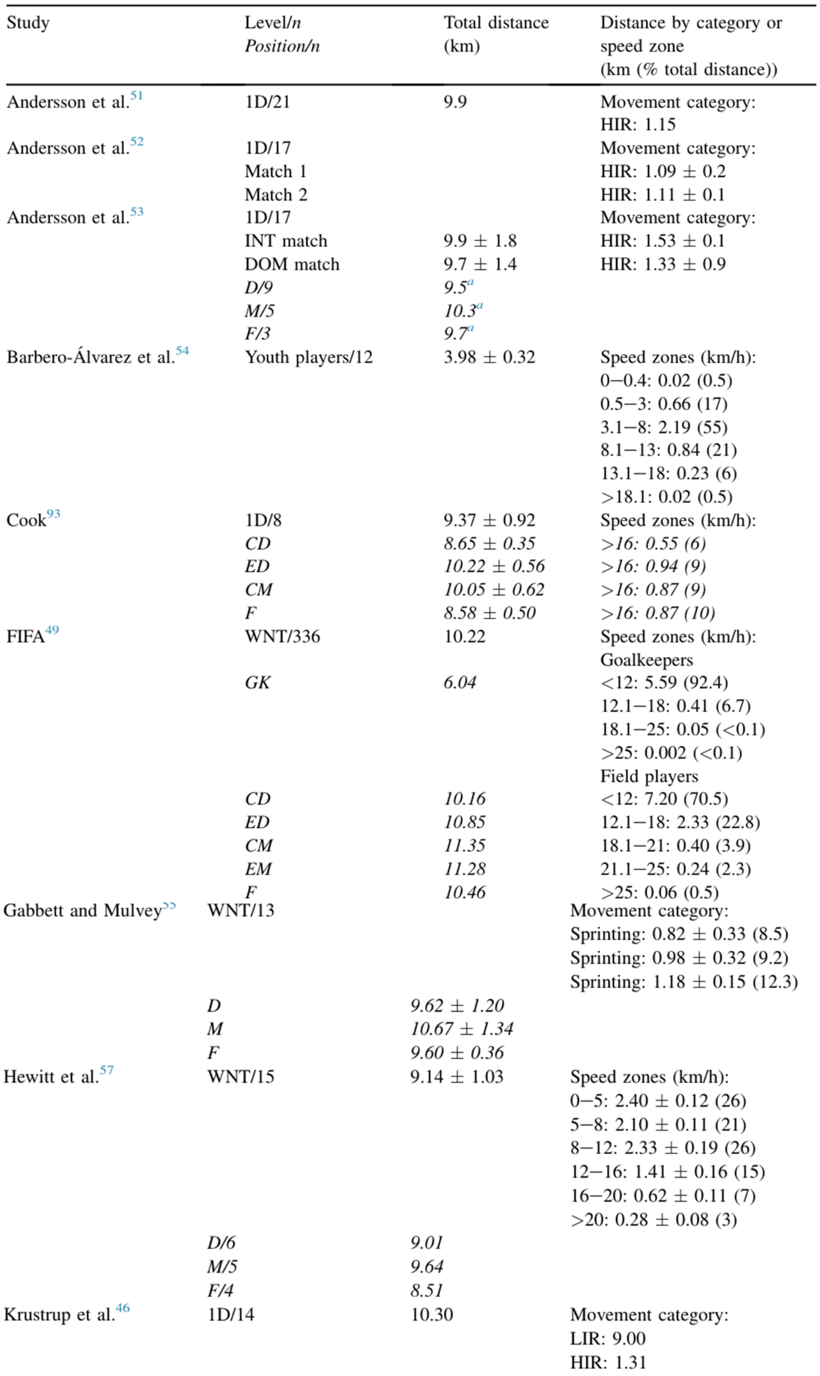


Variable	Attacker	Midfielder	Defender	Comparison *
TD	9882 (9414–10,349)	9536 (8998–10,034)	9039 (8527–9551)	A > D; A = M; M = D
HSRD	1333 (1147–1519)	840 (626–1054)	868 (665–1071)	A > D,M; M = D
SPRTD	633 (524–743)	267 (141–393)	385 (265–504)	A > D,M; M = D

Values presented as means (95% CI), m; TD, Total distance; HSRD, High-speed running distance; SPRTD, Sprint distance. * >, statistically significant difference; =, non-statistically significant difference.

Table 1.1. *Total Distance covered and distances covered during high-speed running and sprinting separated by position.*[8]

Similarly, a review done on female soccer athletes focused on total distance and athlete variability, mentioned how there can be a significant decrease in the total distance covered. One study showed an average 2.7% decrease in total distance in the second 45-minute half compared to the first.[9] The reviewers also noted that total distance and distance covered at different speeds can vary depending on the athlete’s nationality, competitive level, positional role, and method of measurement employed in each study. Table 2 below reflects these differences.



Study	Level/*n* *Position/n*	Total distance (km)	Distance by category or speed zone (km (% total distance))
Andersson et al.[51]	1D/21	9.9	Movement category:
			HIR: 1.15
Andersson et al.[52]	1D/17		Movement category:
	Match 1		HIR: 1.09 ± 0.2
	Match 2		HIR: 1.11 ± 0.1
Andersson et al.[53]	1D/17		Movement category:
	INT match	9.9 ± 1.8	HIR: 1.53 ± 0.1
	DOM match	9.7 ± 1.4	HIR: 1.33 ± 0.9
	D/9	*9.5*[a]	
	M/5	*10.3*[a]	
	F/3	*9.7*[a]	
Barbero-Álvarez et al.[54]	Youth players/12	3.98 ± 0.32	Speed zones (km/h):
			0−0.4: 0.02 (0.5)
			0.5−3: 0.66 (17)
			3.1−8: 2.19 (55)
			8.1−13: 0.84 (21)
			13.1−18: 0.23 (6)
			>18.1: 0.02 (0.5)
Cook[93]	1D/8	9.37 ± 0.92	Speed zones (km/h):
	CD	*8.65 ± 0.35*	*>16: 0.55 (6)*
	ED	*10.22 ± 0.56*	*>16: 0.94 (9)*
	CM	*10.05 ± 0.62*	*>16: 0.87 (9)*
	F	*8.58 ± 0.50*	*>16: 0.87 (10)*
FIFA[49]	WNT/336	10.22	Speed zones (km/h):
			Goalkeepers
	GK	*6.04*	<12: 5.59 (92.4)
			12.1−18: 0.41 (6.7)
			18.1−25: 0.05 (<0.1)
			>25: 0.002 (<0.1)
			Field players
	CD	*10.16*	<12: 7.20 (70.5)
	ED	*10.85*	12.1−18: 2.33 (22.8)
	CM	*11.35*	18.1−21: 0.40 (3.9)
	EM	*11.28*	21.1−25: 0.24 (2.3)
	F	*10.46*	>25: 0.06 (0.5)
Gabbett and Mulvey[55]	WNT/13		Movement category:
			Sprinting: 0.82 ± 0.33 (8.5)
			Sprinting: 0.98 ± 0.32 (9.2)
			Sprinting: 1.18 ± 0.15 (12.3)
	D	*9.62 ± 1.20*	
	M	*10.67 ± 1.34*	
	F	*9.60 ± 0.36*	
Hewitt et al.[57]	WNT/15	9.14 ± 1.03	Speed zones (km/h):
			0−5: 2.40 ± 0.12 (26)
			5−8: 2.10 ± 0.11 (21)
			8−12: 2.33 ± 0.19 (26)
			12−16: 1.41 ± 0.16 (15)
			16−20: 0.62 ± 0.11 (7)
			>20: 0.28 ± 0.08 (3)
	D/6	*9.01*	
	M/5	*9.64*	
	F/4	*8.51*	
Krustrup et al.[46]	1D/14	10.30	Movement category:
			LIR: 9.00
			HIR: 1.31

Martínez-Lagunas et al.[59]	2D/7	9.65 ± 0.86	Speed zones (km/h): <12: 7.23 ± 1.24 (75) 12−16: 1.56 ± 0.35 (16) 16−20: 0.64 ± 0.16 (7) >20: 0.22 ± 0.07 (2)
	D/3	*9.42*	
	M/3	*10.30*	
	F/1	*8.38*	
Martínez-Lagunas et al.[60]	2D&4D/10	7.23 ± 1.47	Speed zone (km/h): >16: 0.63 ± 0.36 (9)
Mohr et al.[61]	Pro players/34		Movement category:
	Top-class	10.33 ± 0.15	HIR: 1.68 ± 0.09
	High-level	10.44 ± 0.15	HIR: 1.33 ± 0.10
Portela Sarazola[47]	U-17 State team/16	5.74−6.77	Speed zone (km/h): >16: 0.20−0.29
Scott and Drust[99]	WNT/30	11.98 ± 1.33	Movement category: Walking: (26) Jogging: (45) Cruising: (13) Sprinting: (3) Other: (13)
	ED	*12.64 ± 0.42*	
	CD	*11.01 ± 1.40*	
	M	*12.97 ± 0.54*	
	F	*11.80 ± 1.28*	

Note: Data are expressed as mean ± SD, unless otherwise indicated.

Abbreviations: 1D = first division; 2D = second division; 4D = fourth division; WNT = Women's National Team; GK = goalkeeper(s); CD = central defender(s); ED = external defender(s); CM = central midfielder(s); EM = external midfielder(s); F = forward(s); M = midfielder(s); D = defender(s); GPS = Global Positioning System; INT = international; DOM = domestic; LIR = low-intensity running; HIR = high-intensity running; U = under.

[a] Average of values reported for international and domestic matches.

Table 1.2. *Overview of studies quantifying the physical demands of women's soccer based on distance.*[9]

While fatigue levels can vary greatly, there is an overall theme of exhaustion after match play. In one study, researchers simulated the fatiguing effects of a 90-minute soccer match consisting of play for 45 minutes, a 15-minute break, and another 45 minutes by simulating two five-minute sequences repeatedly that were recorded from a previous game.[10] This was done with eight amateur soccer players with over 10 years of experience and participated in three to four sessions a week. They simulated the match by selecting a midfielder participating in the whole game and had been on the winning team to collect more conclusive results. Jumping ability was evaluated with a force plate and performed at baseline, halftime, and game end. Robineau et al. found that after modeling a game, there was a significant decrease in sprinting and SJ performance, both at halftime and when the game ended. Interestingly, they did not see a significant change in CMJ, but believe it is due to SJ and CMJ not evaluating the same performance indexes.[10]

A similar study testing within a match focused on the fatiguing effects of performing soccer-specific actions on CMJ and recovery. The soccer-specific actions included changes in direction, making contact, jumping to head the ball, passes (short or long), and making a tackle. Using ten professional soccer players and video match analysis, Nedelec et al. found that during the 72-hour recovery period, CMJ significantly decreased where muscle soreness increased. They also found a significant decrease in CMJ performance when there was a greater increase in performing soccer-specific action.[11]

Researchers find similar results when using a younger population. For instance, a study using 10 youth soccer players with a mean age of 15.8 years also illustrated a significant decrease in jump performance while performing soccer-specific exercises. The jump trials were performed directly before and after a 42-minute soccer-specific exercise test on a non-motorized treadmill to simulate competing in one-half of a soccer match. This study tested CMJ, SJ, and drop jump (DJ) performance on a force plate and saw the greatest reduction in height with the DJ.[12] A different study involving youth and single-leg CMJ performance during a 72 hour period tested jump performance and interlimb asymmetry pre, post, 24-, 48-, and 72-hours after a match. Fourteen elite adolescent male soccer players with a mean age of 17.6 years were asked to perform their jumps on a force plate using one leg. They found that the greatest decrease in performance was directly after a match, with asymmetry returning to pre-match strength at the 48-hour test while jump performance stayed significantly lower.[4]

There are also times when these soccer athletes may have two games within 72 hours, causing a lack of recovery, or a match may involve going into ET to break a tie, making the athlete more fatigued. A study showing the fatiguing effects of what a short period between matches can do to the body tested if an active recovery could improve performance compared to passive recovery. Seventeen female elite soccer players were given two different recovery methods to test in addition to testing changes in jump and sprint performance. Researchers confirmed their hypothesis with the results showing that as CMJ performance decreased after the first match, and it was still reduced prior to the second. They also found that an "active recovery" had no effect on improving their recovery performance prior to the second match.[7] A relatable study testing already exhausted female soccer players, looked at the physical demands of these athletes being required to play in two 10-minute ET periods when a game is tied after the regulation time of 90 minutes. Williams et al. used ten ET and 11 regulation time matches analyzing total distance, high metabolic power distance, speed exertion, heart rate exertion, average heart rate, and energy expenditure to understand the volume and intensity of a match. Incidentally, the results showed that when players had to participate in these ET periods, it added about 20% to their workload, but they were able to maintain their performance throughout by measuring total and high-intensity distances, energy expended, and heart rate. It was deduced that it was likely due to the highly competitive nature of these matches since they were close in score and the researchers tried to stress the importance of developing a recovery strategy in an effort to decrease the risk of injury.[13]

Conflicting research has also been done when determining how taxing soccer can be on an individual. During four succeeding soccer training sessions, nine youth players were asked to perform a CMJ test at the start and end of the session. Researchers hypothesized that there would not be a change in CMJ performance due to the nature of in-season training that was focused moreso on the maintenance of players' physical capacities. Malone et al. found their hypothesis to be true, as there was no statistically significant data showing a difference between pre and post-session jumps. They assumed this may have been due to the shorter nature of the training session, concluding that collecting data over a longer period of time could result in a different outcome.[14]

Defining Fatigue

Reaching a universal conclusions about fatigue is difficult when monitoring any population, including athletes. Possible origins for fatigue can vary as it has the possibility of coming from in the musculature or it could be considered psychological. Also, the sites of fatigue can differ due to the duration and intensity of the activity. A review interpreting fatigue allocated participants into two groups, performance fatigability and perceived fatigability.[2] Performance-related fatigue is dependent on the muscles and the nervous system's ability to respond when called to activate. Perceived fatigue can be based on an individual's homeostasis and psychological state. Figure 1 illustrates this difference, providing the characteristics for each element of fatigue.

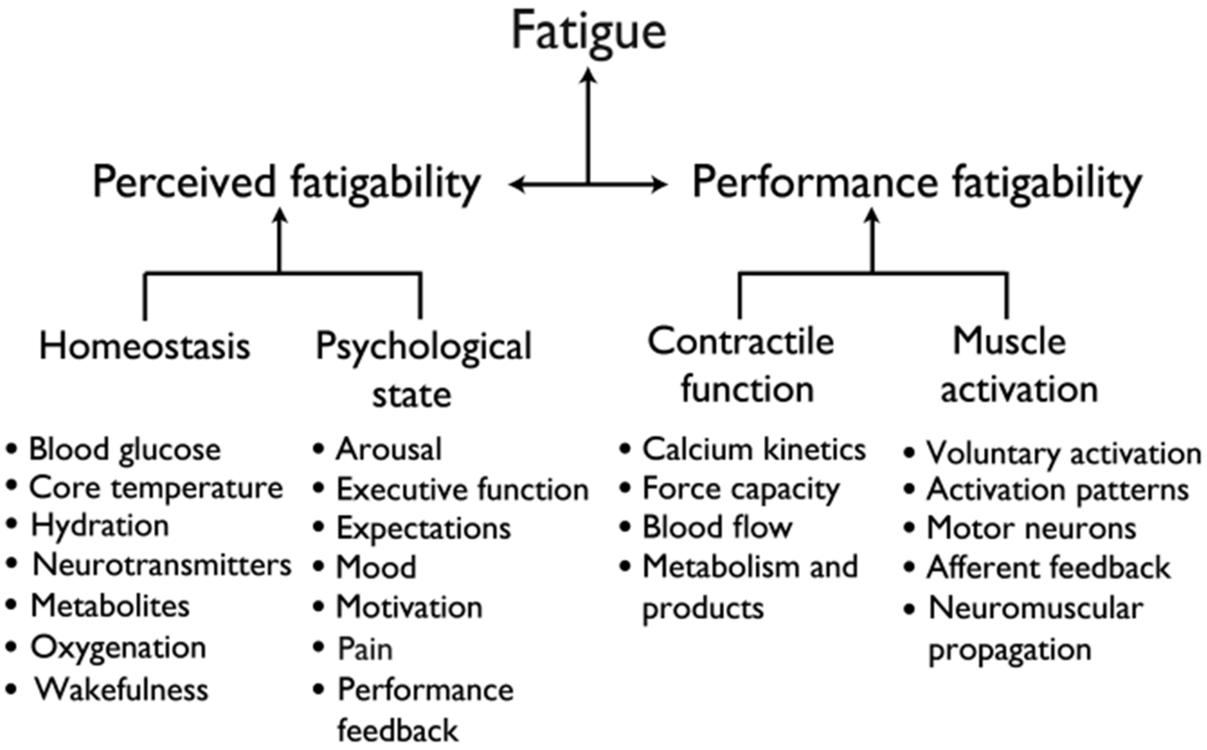


Figure 1.1. *Suggested Taxonomy for Fatigue*[2]

Enoka et al. went on to state that it is believed that in order to successfully understand fatigue, it should be defined as a symptom, meaning it can only be documented if the individual reports feeling fatigued. For the purposes of this review, fatigue will be defined as an exercise-induced reduction in voluntary maximal force or power output or an increase in the effort required to sustain a given activity. This definition combines both central and muscle fatigue. A corresponding study reviewed six different techniques to accurately gauge an athlete's fatigue.[3] These methods included self-reporting, the autonomic nervous system, physical performance, neuromuscular function, joint range of motion/flexibility, and biochemical/hormonal/immunological. Focusing on how neuromuscular function can be used to monitor fatigue, Thorpe et al. found that CMJ and SJ are routinely used, and studies report a significant decrease for up to 72 hours. When using CMJ to gauge performance, jump height cannot be looked at alone as they found there may be a lack of sensitivity to distinguish changes in training load. The parameters that should be incorporated for more conclusive results include eccentric contractions, concentric contraction, total duration of jump, time to peak force/power, and the ratio between flight time and contraction-time. Other non-invasive methods for measuring fatigue that were deemed sensitive enough include self-reporting measures, the autonomic nervous system examining heart rate, and joint range of motion/flexibility.[3]

Vertical Jump as a Measure of Fatigue

One noninvasive measure a team sport can utilize to gauge performance is vertical jump performance. Gathercole et al. employed this way to gauge performance in a group of twelve elite rugby players, undergoing CMJ testing once a week during a 6-week training session where the training load was progressively increased. The aim of this study was to understand if CMJ testing could be used as a way to assess neuromuscular function and fatigue. Researchers saw that as training increased, there was a decrease in CMJ output and alterations in CMJ mechanics. By the end of the 6-week training period, the results showed that as training load increased, jump height decreased, confirming their hypothesis.[15]

While experimenting on whether training load would induce fatigue and change vertical jump performance, there is also the possibility that an individual’s initial strength could alter jump performance results. A study was done to find whether different intensities of muscular fatigue would affect vertical jump performance and if the initial amount of leg strength an individual had influenced this response.[16] Researchers had twelve male athletes split into two groups based on strength tests for their leg-press and vertical jump 1-repetition maximum (1-

RM). They were then fatigued by lifting 50, 70, or 90% of that value until exhausted. When vertical jump was measured before and immediately after being fatigued, they found that the distance jumped, and the work produced decreased significantly. Due to these findings, they were able to conclude that the larger reduction in strength would lead to a larger reduction in vertical jump performance, regardless of initial leg strength. Watkins et al. looked at a similar method by inducing fatigue in 17 male athletes using 80 to 85% of their calculated 1-RM for back squats, Romanian deadlifts, leg press, hang cleans, and push press. During this study, the athletes had to perform vertical jumps before and after their exercise regimen with only 48 hours between sessions. It was observed that not only did total training load decrease going from session 1 to session 2 but so did vertical jump height. They were also able to correlate back squat volume and vertical jump height, finding that as one decreased, so did the other.[17] A comparable study tested the effects of lower-body fatigue on vertical jump and balance performance by using 24 male and female participants testing their CMJ, SJ, and balance. They were given three trials of each type of jump in a randomized order on a force plate, jumping as high and as quickly as possible, once before the fatigue protocol and once after. It is also worth noting that CMJs were performed with an arm swing instead of being asked to keep their hands on their hips. The participants were then fatigued by performing SJ continuously for 60 seconds.[18] Cooper et al. found there were significant differences between pre and post-jump data, having greater jump performance before the exercise, and found balance was not significantly affected. They concluded that since there was such a large decrease in jump performance after only 60 seconds of exercise, suitable rest time should be considered when prescribing a training regimen to avoid the risk of injury and improper movement. Interestingly, CMJ is usually performed without an arm swing to avoid the motion conflicting with jump performance, but the mention of this limitation was not included.

To better determine whether an arm swing has an influence on jump height, there have been studies done on CMJ with (extending the arm upward during the jump) and without (hands on the hip) arm swing. A study testing the reliability of CMJ specifically evaluated the effect of an arm swing (CMJAS) or no arm swing (CMJNAS) on whether it would affect the reliability of CMJ on gauging performance.[19] Twenty-two male and female basketball players were asked to perform each type of CMJ three times before a strength training session, one week apart during an off-season training period lasting 2 weeks. Both types of CMJs were performed on a force plate and both intrasession and intersession variables were analyzed.[20] Heishman et al. was able to conclude that CMJAS would be better for assessing long-term changes, like assessing performance between training phases, while CMJNAS would be best for acute changes to gauge neuromuscular readiness and fatigue to monitor athletes throughout a season and prevent overuse.

Contradictory studies have also been done, one involving match-related physical performance and vertical jump performance. Eighteen professional soccer players completed an incremental running field test, a vertical jump performance test (VJP), and a repeated-sprint ability test (RSA). While there was a significant correlation between the mean RSA and very high intensity running (VHIR) and sprinting, they did not find significant differences between RSA and VJP, concluding vertical jump was not an accurate way to assess performance. Another conflicting study examined the reliability and extent to which CMJ can be used as an assessment tool for fatigue-induced changes in neuromuscular function and hypothesized that the typical way of using CMJ may not accurately reflect fatigue.[21] Typical CMJ (CMJ-TYP) includes variables such as peak power, peak force, peak velocity, and flight time, whereas alternative CMJ (CMJ-ALT) includes eccentric and concentric duration. Eleven male college-level athletes participated in this study, where eight underwent a fatiguing and reliability portion and three of them completed only the reliability portion. For the purpose of this review, we will only focus on the fatiguing portion. The fatiguing high-intensity running protocol was used to simulate a similar neuromuscular load to team-sport activities and then performed 6 CMJs, collecting the most consistent 4 taken immediately, 24, and 72 hours post-exercise. Gathercole et al. found their hypothesis to be incorrect, concluding that most CMJ variables did show decreased neuromuscular function and would be a reliable and noninvasive way to show neuromuscular fatigue.

In addition to testing the effects of training load on jump performance, researchers also studied whether aerobic-based training had the same decreasing effect. A study focused on nine high-level male sprinters who were tasked with performing five, 60 m sprints being allotted only a maximum of a 3% speed loss, with 6 minutes to rest between sets.[22] After each sprinting session, they performed one CMJ and their blood was sampled to determine lactate and ammonia concentrations. They found that CMJ height pre-exercise was significantly different post-exercise, decreasing after each repetition. Figure 2, from Jiménez-Reyes et al. shows the increasing loss of vertical jump height and increasing sprint time during the protocol. This shows that the two measures of fatigue during a high-intensity exercise session are closely related.

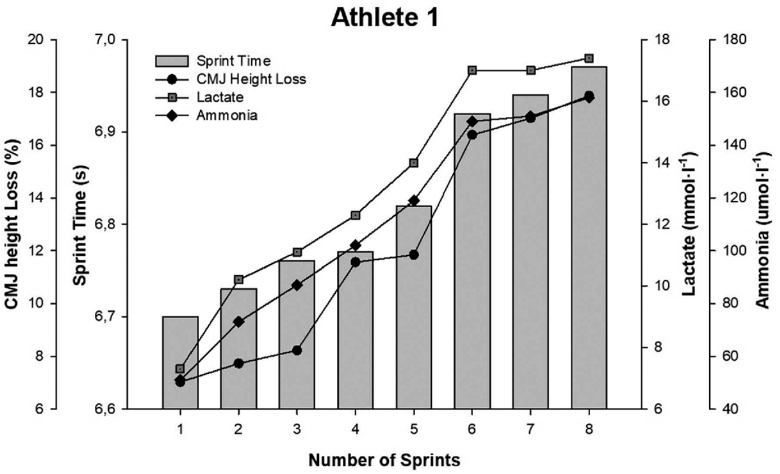


Figure 1.2. *Progression of sprint times, CMJ height loss, blood lactate, and ammonia concentrations for a single athlete.*[22]

Vertical Jump and Training Programs

Some studies have used vertical jump performance in other ways. Researchers are studying the effects of different types of training programs on vertical jump performance and whether it will increase after a training load or session is complete. While these studies are not directly related to fatigue, they do help establish vertical jump as a measure of neuromuscular performance. A study done using thirty-five male individuals were divided into three groups. One consisted of twelve soccer players following a combined training program (COM group), one group had eleven soccer players doing only resistance training (STR group), and the final group was a control (CON group) of twelve that were randomly selected physical education students that were moderately active due to their class, but did not have any sport training background. The goal was to assess the effects of a combined resistance and speed training program on running velocity and vertical jump performance. CMJ, SJ, and DJ performance data were all collected without using arms and with a force plate. The results showed that a combined resistance and running training program in the same training session increased both SJ and CMJ in the soccer players. This was determined by the COM group performing significantly better than the STR or CON groups in the 30-meter dash, SJ, and CMJ. From this, Kotzamanidis et al. were able to conclude that these training sessions could be more effective than regular resistance training programs to increase running speed and jumping ability.[23] There was a comparable study done looking at the effects of a 12-week lower-body power training program using 12 athletes and 18 untrained males on power-, force-, velocity-, and displacement-time curves of CMJ. The results showed that for power-, force-, velocity-, and displacement-time curves there was a significant difference between those who were considered experienced jumpers and inexperienced non-jumpers during the CMJ movement.[24]

Plyometric-specific training programs have also been considered when determining whether vertical jump performance will be affected. A study done on 44 male physical education students with no history of lower limb injury were split into four groups: No Regulation Group (nRG), Regulation Group (RG), Yoked Group (YG), and the Control Group (CG). A six-week regimen of plyometric training without adjusting the training load was given to the nRG group without considering their fatigue levels. The RG group was given the same program, but the training load was adjusted based on the participant's vertical jump performance before the start of a session showing signs of fatigue. The YG also adjusted their training load similarly to the RG group, but their fatigue was not taken into account. All groups had their CMJ and SJ tested using a jump mat before each training session began and by the end of the six-week training period. The results showed that vertical jump performance was significantly lower in the nRG and YG groups compared to the RG group.[25] A similar study trying to understand the effects of plyometric training used a program to test peak vertical ground reaction force (VGRF) and kinetic jumping characteristics. 20 recreationally active college females with at least three years of organized basketball experience were evaluated on their jump performance and VGRF during a CMJ for maximal height on a force plate. This training program lasted six weeks, but after completing it, researchers did not find any significant data suggesting jump and landing performance improved with a plyometric training program.[26]

Reliability of an Accelerometer for Vertical Jump

Inertial measurement units (IMU) have become more popular in recent years as it is a device that usually contains an accelerator or a gyroscope, can be worn by participants, giving an ability to collect and see immediate results, and is a small, discrete way to record data without having to be in the laboratory setting or bothersome to participants. While most of the literature supports the use of these devices, it is still being debated whether it can give a reliable and valid measurement of vertical jump height. One of the major appeals that come with the use of an IMU device is that it can be customized and built to be the type of sensor that is necessary for what a researcher may want to investigate. They can also be distributed to a large number of players and easily used in the field. As such, many collegiate and professional teams have players wear IMUs during training and competitions.

There was a study done solely on the development of IMUs and the framework for evaluating vertical jump based on estimated flight time. The IMU device (accelerometer and gyroscope) used in this study had an accelerometer, a gyroscope, and a magnetometer. Below is the figure depicting the IMU device with regard to the coordinate system (Figure 3).

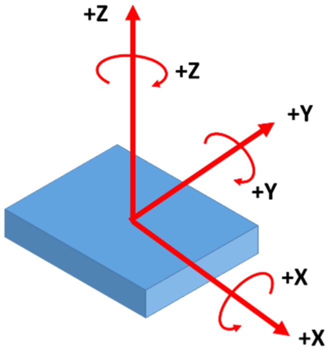


Figure 1.3. Orientation of the IMU device used by Garcia et al.[27]

The IMU was worn around the waist of a male 23-year-old, in the lumbar region, as it is where the center of mass of an individual is located, and there were pressure sensors placed on his forefoot. He completed five squat jumps with ten seconds to rest in between. The results showed that the difference between the IMU and the pressure sensor time of take-off and landing was on average below 0.06 seconds, which they considered an acceptable error. There was also no significant difference in average flight time and height readings. Garcia et al. concluded that the use of an IMU device could be advantageous when evaluating an individual's vertical jump and further research should be conducted as it was deemed user-friendly for athletes.[27]

Besides the use of pressure sensors, a common way to record different VJ values to test the validity of an accelerometer, results usually involve the use of a force plate. This form of comparing data seems more apparent in the literature as the force plate is considered to be the "gold standard" and has been proven to give accurate results. The issue with the force plate is that while it can be utilized in the laboratory setting, it prevents the ability to collect real-time data in the field. For instance, there was a study done using a vertical jump mat compared to a force plate and a Vertec VJ (a jump and reach measurement device) with the results showing some conflicting evidence.[28] A Vertec device measures the difference between the fully extended standing reach height and the maximal vertical jump-and-reach height. Whitmer et al.

hypothesized that the jump mat would give the same height and flight time results as the force plate and significantly lower height measurements compared to the Vertec tester; however, results showed that the jump mat indicated the participant's flight times were significantly longer (consistently about 105ms longer) than that of the force plate but it did give similar VJ reach height measurements as the Vertec tester. It was also recorded that when comparing VJ heights from the VJ mat and the Vertec tester, there were no significant differences. They concluded that while the program algorithm for flight time was off by about 100ms and could be fixed by altering the equation used, the research still indicated that the VJ mat would be insufficient for elite-level athletes. It was also suggested that it may be ideal to use the Vertec tester and jump mat together as the literature shows that people tend to jump higher when they are trying to reach for a goal.[28]

Since the force plate has proven to be reliable, it has been used to test the reliability of accelerometers within IMU devices. A study done on a diverse age group of 41 women, men, and children, ages 6 to 77 years old, completed CMJs wearing both an IMU on their lower lumbar region and using a jump mat at the same time to test the agreement between jump height.[1] Jump height was estimated using flight time, take-off velocity, and concentric net impulse to ensure accuracy. These participants completed two maximal effort CMJs within 5% of each other, making sure to keep their hands on their hips to reduce the risk of upper body contribution, with 30 s rest in between. The results showed that the estimated jump height from the IMU was parallel to the jump mat-derived heights determined by vertical acceleration and flight time. Below is a figure depicting this trend (Figure 4). Based on this evidence, Rantalainen et al. concluded that the IMUs could be used to evaluate and monitor athletic performance.[1] A similar study done using a group of 40 similar aged university students at different activity levels were used to assess three different devices, the Vertec, Just Jump system, and Myotest for measuring CMJ height reliability for both intrasession and intersession. Intrasession was characterized by trial-to-trial reliability while intersession was session-to-session. The Just Jump System determines height by measuring flight time that is recorded by microswitches located within the mat that is used. These subjects completed three maximal-effort CMJs during two testing sessions, separated by 24-48 hours. Nuzzo et al. found that the Myotest demonstrated the best intrasession and intersession reliability for both males and females.[29]

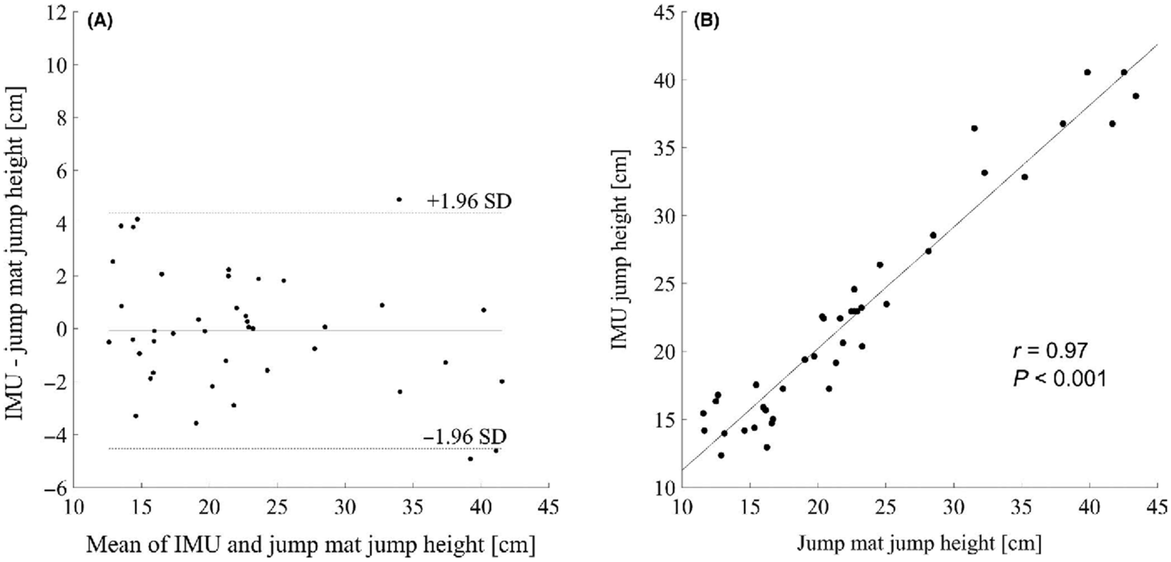


Figure 1.4. *Reliability data generated by Rantalainen et al*[1] *showing Bland-Altman (A) and Scatterplot (B) relationship and correlation.*

Adolescents are another group researchers must investigate, specifically as their age and experience level can change the results for an accelerometer. A study was done comparing jump height estimates for adolescents using a hip-worn IMU and a jump mat.[30] 99 healthy males and females aged 10-13 years old participating in a cohort called HAPPY (Healthy, Active Preschool & Primary Years) where they attended one testing session. These participants completed three maximal effort CMJs with 30 seconds of rest in between on a jump mat while wearing an IMU on a belt. It was located directly above their hip and were instructed to keep their hands on their hips. The major findings from this study include that the flight time from the IMU had excellent concurrent validity with the jump mat, but the maximal velocity was only in fair agreement; however, they did state that the systematic differences between the two devices cannot be directly compared unless attentively calibrated. Overall, the researchers concluded that jump height derived from flight time would be better compared to velocity measurements when utilizing IMUs for adolescents.[30] Another adolescent cohort of 19 female sub-elite youth soccer players had to complete three trials of CMJ and SJ respectively while jump height was recorded using a Gyko inertial sensor system and examining its validity against a force-plate and an Optojump photoelectric cell system (another criterion device frequently used in the field). Lesinski et al. hypothesized that the Gyko system would be a valid tool, but their results showed they were only partially correct. While there was some agreement, there was too significant of a systematic and high random bias from the Gyko system and regression equations had to be utilized to find a more accurate jump height. While they do not state that the age and size of the cohort were the issues, they do mention that the equations used were specified for this population's age range, and for female sub-elite youth soccer players.[6]

There is also a group of researchers who chose not to limit their subject group to a particular age range and widened it greatly to test the reliability of the Myotest accelerometric system and similar type of IMU device. 44 male basketball players, ranging in age from 9 to 25 years old, performed a series of SJ and CMJ repeatedly during two identical test sessions that were separated by 2-15 days. Vertical jump height data was collected by wearing the sensor around their hip, having both the Myotest system record flight time (Myotest-T) and vertical takeoff velocity (Myotest-V) and compared it to ground-based photoelectric cells (Optojump) by performing the jump on a force platform. The outcome showed that the Myotest-T had an excellent validity compared to Myotest-V. This is due to height being calculated by using the flight time interval between peak positive and peak negative vertical velocity.[31]

The literature supports the use of an IMU device for those individuals who are not considered athletes or elite, likely because there is a concern that the higher an individual can jump, the more inaccurate the device can be. In an attempt to make wearable IMUs available to a more advanced exercise population, researchers have used participants involved in recreational exercise to start to bridge that gap. A study done with twenty-seven recreationally active males, competing in at least one team sport match per week, wore a torso-worn IMU device while completing their CMJs on a force plate.[5] While performing the CMJ, they were told to jump with their hands on their hips and were given a 60-second rest in between jumps. Jump height was calculated based on maximal velocity and flight time. The results showed that there were significant differences between force plate and IMU-derived estimates of jump height and power. The validity of the IMU results included calculating jump height from flight time, take-off velocity, and mean concentric power. Those values were then compared to the coinciding force plate data from two sessions. Rantalainen et al. found that the repeatability of the IMU was good and matched values recorded by the force plate and that the flight time jump heights showed better coinciding validity and repeatability than maximal vertical velocity jump height.[5] Similarly, a study done on twenty-eight college students who were required to have trained for at least ten years to participate in this study, performed CMJs with a torso-worn IMU five times with a three-minute rest in between each trial.[32] The goal of the study was to understand whether an IMU- device containing a 3D accelerometer and a 3D gyroscope with stereophotogrammetry, a method to estimate 3D coordinate points, could determine maximum jump height in a CMJ.

They estimated jump height by imitating the trajectory of the center of mass of an individual using two different methods to calculate. One method used the maximum vertical displacement of the center of mass in a participant during the free-fall motion. The second method used the equation of vertical displacement of the center of mass also during free-fall. The values from these methods were then compared using an estimate of the 3D coordinate points to show which would be most accurate. It was found that the former was the most accurate due to the second method taking into account the rotation of the trunk, and therefore underestimating jump height.[32]

Another group of recreationally active athletes were asked to perform five individual CMJs while using an accelerometer (Myotest), an optic timing system (Optojump), and a force plate using flight time and force impulse algorithm. These 33 university students conducted these jumps measuring for what researchers in this study considered explosive strength indicators. This includes jump height, peak force, peak velocity, and peak power during the CMJ. The results showed that while the accelerometer can be a valid tool for evaluating CMJ height and an athlete's performance, it should not be used to measure peak force, velocity, or power nor be compared against other methods due to a bias which over or underestimates results greatly. They did indicate that placing the accelerometer as close to the center of mass of a subject as they could, in theory, make for the most accurate results; however, the accelerometer recorded more agreeable data when attached to a barbell and with a heavier load when the participants jumped. This could indicate that future research could involve using some type of bar at the shoulders to make the center of mass heavier and possibly closer to the actual center for better results, but the outcome is unknown.[33]

Research has gone further to determine the reliability and validity of this tool to be utilized with athletes, as their elite levels have the potential to skew results. A study was conducted using ten athletes, seven of whom were track and field athletes and three of whom were basketball players. They were asked to complete a total of 15 drop jumps: five jumps, from three different heights and two minutes of rest in between, using an AMTI force platform and wearing an IMU worn at the ankle. Jump height was estimated using the IMU-based vertical jump direction of the landing and take-off acceleration. Jaitner et al. found that 94% of the jumps were detected correctly and concluded that the IMU could be used on athletes considered advanced or elite. They also suggested that the device could be utilized for training purposes, jumping events, and monitoring fatigue.[34] A similar study using global positioning system (GPS)-embedded accelerometers tested their reliability on field-based running measures to three typical conditioning sessions of strength, endurance, and speed. 18 elite soccer players performed CMJ and adductor squeeze strength before and immediately following each session. The results showed that after all the sessions, there was a small decrease in adductor strength and a small increase in CMJ performance after speed and endurance sessions. Additionally, there was an unclear change after a strength session. Buchhiet et al. concluded that running-specific measures when assessing neuromuscular function with this type of accelerometer showed tolerable levels of reliability and may be limited to that. Overall, it is likely that noticing a change would be session-objective dependent, meaning it could be the activity or the athlete being too advanced causing this issue.[35]

Reliability, Responsiveness, and Feasibility

To be useful in the field or in a laboratory, a test, instrument, or measurement system must be reliable, applicable and have the ability to discriminate (i.e. sensitivity). Reliability is a difficult term to define because just like fatigue, it can have a multitude of definitions. One paper discussing the concepts of measured reliability and minimal important chance examined the different types of reliability.[36] The review states that measurement reliability can be regarded as the consistency or stability of a measurement taken within a single session (intrasession reliability) or between sessions (intersession reliability). This is due to all measurements having some magnitude of error whether it is attributable to the instrument, subject, the evaluator or randomness, so values can fluctuate with serial evaluations. Other terms that can describe measurement reliability include agreement, repeatability, precision, consistency, and minimal detectable change keeping in mind that reliability refers to the extent to which a test or instrument provides a measure that is free of error over repeated trials. Alternatively, relative reliability describes the consistency of the rank or position of an individual within a group across repeated assessments, being the most frequently reported statistic and usually shown by using intraclass correlation coefficient (ICC). Riemann et al. states that even ICC itself can be difficult to interpret because there is no universal standard currently excepted. Generally, though, if ICC is greater than 0.75, the test is usually considered reliable.[36] A similar study is trying to quantify test-retest reliability using ICC and SEM. Weir defines reliability as the consistency of a test or measurement.[37] He goes on further to mention how while this concept seems easy, quantifying the reliability can be unclear especially in sports science literature due to the fact that reliability can be assessed in a variety of different contexts.[37] For the purpose of this study, test-retest reliability is used. That is the extent to which test scores are consistent from one measurement period to another[36, 37].

The test, instrument, or measurement system must also be applicable to the circumstances and situation where it will be used. That is, can it be easily applied to the population of interest, in the environment in which they are functioning. In addition, applicability describes "the extent to which the results are likely to have an impact on practice."[38, 39] On the other hand, responsiveness to change (or sensitivity) can be characterized as the ability of a test to correctly identify or characterize a known condition.[40] In the context of CMJ testing, it is important that the test be easily administered in the field, the results provide meaningful data to the practitioner and the measure detects conditions such as fatigue.

Based on the above, the following questions should be answered. First, are measurements of CMJ height using an accelerometer reliable? Are the outcomes consistent within a testing session and across testing days? Second, can a test of CMJ height be administered on a regular basis within the context of soccer training and playing matches? Third, do changes in CMJ height reflect conditions thought to elicit fatigue, such as soccer training and/or competitive matches.

Conclusion

Overall, cataloging vertical jump measurements can be a useful task when trying to understand fatigue and physiological monitoring for team-sport athletes like soccer. These athletes have such a diverse workload that depends on the season, their position on the field, and more. Using vertical jump to gauge fatigue level takes out the need for athletes to miss out on practices and matches because they are avoiding overuse and overtraining injuries. Additionally, IMUs are being proven to be a reliable and valid method to collect vertical jump data in the field. Avoiding the need to go into a laboratory to report these values helps to find the immediate consequences of a training session or soccer match and could help prevent injury as well. Further research can be done using vertical jump to test the probability of common soccer injuries, like a knee injury, and whether a decrease in vertical jump performance would lead to a greater likelihood of this occurring. Wearable IMU research can also be supplemented by more research on their reliability and validity for recording vertical jump data. This study will further research whether the conditions thought to cause neuromuscular fatigue will also be reflected in a diminished vertical jump height. In turn, this would allow one to use changes in vertical jump height as a measure of fatigue in female college soccer players.

METHODS

Design Overview.

This thesis consists of two studies. The first was designed to assess the within and between-day reliability of accelerometer-based countermovement jump measurements. For within-day reliability, subjects performed three countermovement jumps without an arm swing using the 3-jump protocol described below. Jump heights were then compared between the jumps. Consistency between jumps was qualitatively interpreted as the method having acceptable within-day reliability. The subjects also performed the 3-jump protocol on 5 different days (each separated by one week). The small difference between peak height across days was taken as suggestive of good between-day reliability.

The second study was designed to determine the applicability of the accelerometer-based countermovement jump as a measure of fatigue induced by participating in soccer training and matches. This was accomplished by assessing jump performance before and after exercise bouts designed to induce fatigue. First, vertical jump performance was assessed on five consecutive days of "spring" soccer training that included substantial fitness training. Vertical jump height was again assessed after a two-day recovery period. Significant decreases in performance across the days with recovery of performance after rest days would suggest acceptable applicability of the method. Next, vertical jump height was measured before and after competitive soccer matches. Significantly decreased performance in those players playing a full match, coupled with no change in the reserve players was taken as further evidence of applicability of the protocol to assess fatigue.

Subjects, Equipment, and Analysis

Subjects. A total of 40 members of the Virginia Tech Women's Soccer team participated in this study (66.7 ± 8.7 kg, 169.8 ± 5.6 cm, and 20.3 ± 1.7 years of age). Due to the timeline of data collection, not all subjects participated in all aspects of the project. Prior to testing, all procedures were approved by the Virginia Tech Institutional Review Board and informed consent was obtained prior to data collection. Testing was done as part of regular training sessions or matches.

Equipment. All subjects wore a STATSports APEX unit that includes an 18Hz GPS, 952 Hz accelerometer, and 952 Hz gyroscope. The unit was situated on the upper back over the second thoracic vertebra using a manufacturer-provided vest (Figure 3.5). Previous work has established the validity and reliability of running speeds and distances covered in these units.[41] After each training session or match, the data were downloaded using the manufacturer's software (APEX). Raw speed, acceleration, and gyroscope data were then imported into a custom MATLAB program for subsequent analyses.

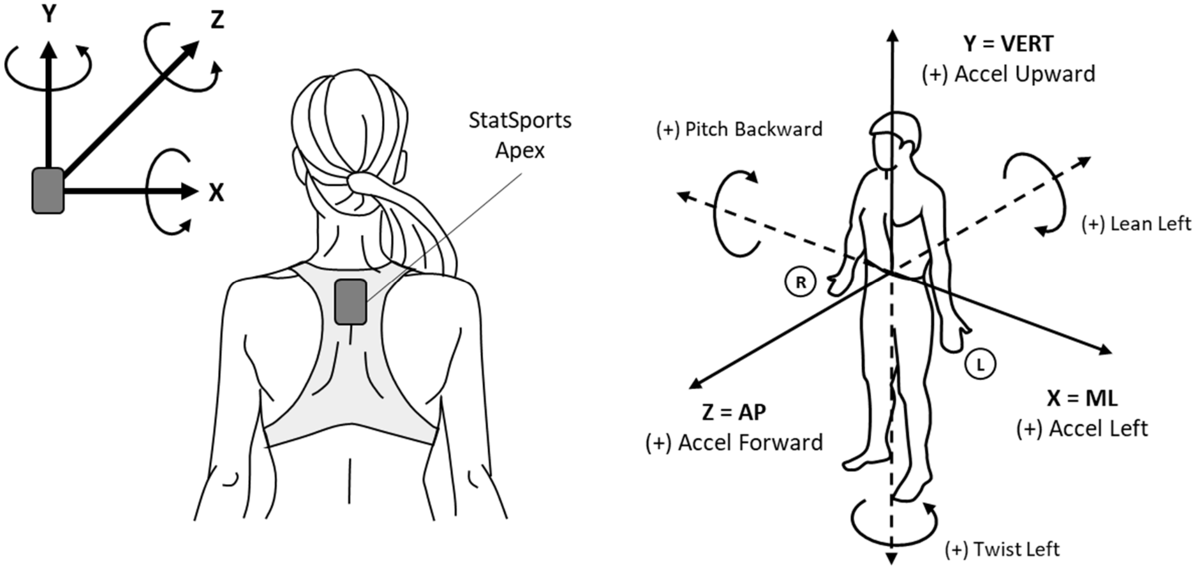


Figure 3.5. Placement and orientation of the STATSports device.[42]

Raw Data Analysis. The APEX software presents the accelerometer and gyroscope data at a sampling frequency of 100 Hz. To improve resolution, data were resampled to 1000 Hz. Next, orientation of APEX data from local to global reference frame was performed using a six-axis Kalman filter via a MATLAB routine that fuses accelerometer and gyroscope sensor data to estimate angular velocity and device orientation. Accelerometer data was then bandpass filtered using a 4th order Butterworth filter (0.9 – 20 Hz) to remove accelerometer drift and noise, respectively. Lastly, vertical velocity was computed using trapezoidal integration of the vertical acceleration signal.

To determine take-off (TO) and touch down (TD) times of each jump, the zero crossings of vertical acceleration that corresponded to peak positive and negative vertical velocities were identified (Figure 3.6). To increase the precision of these times, a linear equation was fitted through the two acceleration points before and two after detected peak velocities. Interpolations of this relationship at zero acceleration represent TO and TD (Figure 3.6). Flight time (FT) was determined as the difference between TO and TD. Jump height was computed as below where *g* is gravitational acceleration (-9.8 m/sec^2).:

$$CMJ\ Height = g * \left(\frac{FT}{2}\right)^2$$

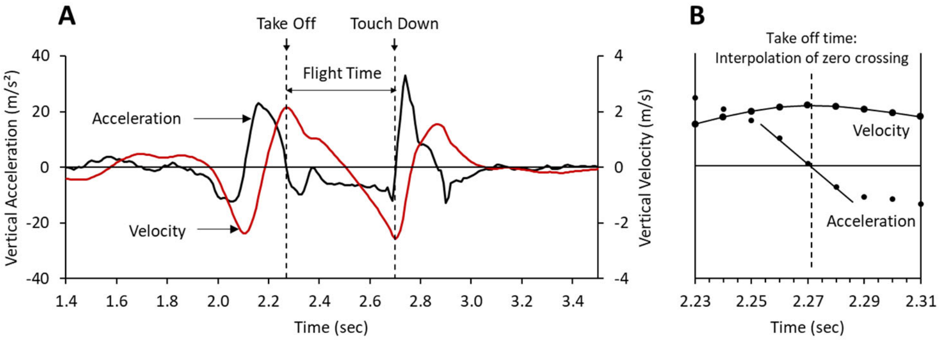


Figure 3.6. *A – The method developed for detection of flight time using accelerometer values. B – Interpolation of take-off time.*

Study 1: Consistency

Three-Jump Protocol. A three-jump protocol was conducted after a warm-up consisting of dynamic stretching, jogging, and changes of direction movements. Immediately following the warm-up, players were instructed to place their hands on their hips and execute a countermovement squat jump, giving maximal effort CMJ. The depth of the squat was self-regulated. The jump was repeated three times with 5-7 seconds between each jump. Players performed the three jumps as a group, with each jump initiated with a verbal command from the coaching staff. The total time required for the task took less than 30 seconds (Figure 7).

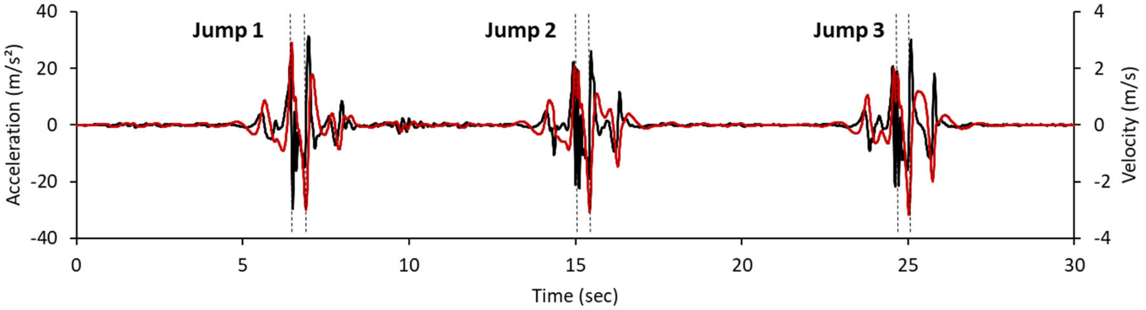


Figure 3.7. Performance of the three-jump testing protocol.

Within Day Consistency. The consistency of vertical jump heights was assessed within and between days. Within-day reliability was determined by comparing the three jumps performed during the protocol. For this aspect of the study, 30 subjects participated (169.561 ± 4.972 cm, 66.867 ± 8.251, 20.1 ± 1.8 yr, means ± SD), performing the jump protocol on eight separate days. This resulted in 240 measurements. Consistency between days and efforts was determined by comparing mean values, and calculating intra-class correlation coefficients (ICC) and coefficients of variation (CV).

Between-day Consistency. Consistency between days was determined using peak CMJ height values obtained on separated days. For these measurements, jumps were performed at the start of five consecutive training weeks (Mondays) following two off-days. This was done to minimize fatigue due to prior training. 32 subjects participated in this aspect of the study (169.521 ± 5.075 cm, 66.186 ± 8.220 kg, 20.1 ± 1.6 yr). This resulted in 160 measurements. Consistency between days and efforts was determined by comparing mean values and calculating intra-class correlation coefficients (ICC) and coefficients of variation (CV).

Study 2: Application

Changes in CMJ Height Within Training Days. Initially, changes in CMJ height resulting from a single training day were determined. CMJ height was recorded at the beginning and end of each high training load session that was designed to induce fatigue. The day 1 training session was conducted after two "off-days," compromising both high intensity and high-volume training. Technical training and small-sided games were followed by fitness drills consisting of repeated high-intensity running efforts. On this day, the 3-jump protocol was administered before training and again within 3 minutes after completion of the fitness drills. Twenty subjects participated in this session (169.125 ± 4.571 cm, 67.081 ± 8.220 kg, 20.2 ± 1.7 yr).

Changes in CMJ Height Across Training Days. Next, CMJ height values were recorded across an eight-day training period where subjects trained for five consecutive days (Monday thru Friday, days 1-5). They were given two off days before beginning a subsequent week of training. CMJ height values were then recorded on the first day of the second training week (Monday, day 6). Due to the nature of off-season training, we anticipated daily fluctuations in training load that would result in varying levels of fatigue and varied CMJ height changes the subsequent day. All training sessions began at 08:00 with a standard warm-up. Sessions consisted of a mixture of technical training, small- and full-sided scrimmages, as well as fitness drills. Following each session, all players participated in a cool-down that included light stretching. Thirteen subjects completed this aspect of the study (169.368 ± 5.530 cm, 69.257 ± 8.635 kg, 20.2 ± 1.6 yr).

Training load for each session was evaluated using the STATSports APEX software. Two metrics that were used as a representation of training load including total distance (the total distance covered during the session while walking and running), and high metabolic load (HML) distance (the distance covered performing high-intensity activity above 25.5 W/kg). Ratings of perceived effort were collected immediately following each session using a 10-point scale.[37] To estimate pre-training readiness, a recovery score was obtained prior to jumping. Players were asked to rate “How well are you recovered?” on a 1–10-point scale. Using this scale, 1 = “very well recovered,” 5 = “adequately recovered,” and 10 = “very poorly recovered.” Analysis of variance (ANOVA) were used to compare values between days.[43]

Changes CMJ Height During a Match. To assess performance changes due to match play, CMJ values were recorded before and after competitive matches. Pre-match data included collecting CMJ height immediately after a normal warmup (similar to the training day warm up). Post-match was collected within ten minutes of the end of a match, prior to the players’ cool down. For this aspect of Study 2, 28 players participated (170.456 ± 5.625 cm, 67.049 ± 9.601 kg, 20.4 ± 1.7 yr) in a total of 5 matches, resulting in a total of 140 player • matches. They were divided into three groups, Full-Time players who started the match and played at least 80 min, Part-Time Players who played between 20 and 75 min, and Reserves who did not play in the match. Match loads were also assessed using the STATSports APEX software as described earlier. Differences in CMJ height in the three groups were evaluated by a 2-way, repeated measures ANOVA (measurement interval vs group) with a Tukey’s post-hoc exam (if indicated). Relative changes in CMJ height (pre-post) were compared to total and HML distance covered during the match earlier using Pearson-Product moment correlation.

Statistics. For all statistical tests, significance was established at $p<0.05$ level of significance.

RESULTS

Study 1: Consistency.

Within-Day Consistency. Comparisons of CMJ heights from jumps performed within and between days are shown in Figure 4.8. As can be seen, the three values recorded on the same day are closely associated. When there was noticeable variability within a day, it resulted from a single jump being underperformed when the two others were similar. Pearson correlations between jumps 1 and 2, 1 and 3, and 2 and 3 were 0.980, 0.982, and 0.963, respectively. Mean values and consistency results are shown in Table 4.3.

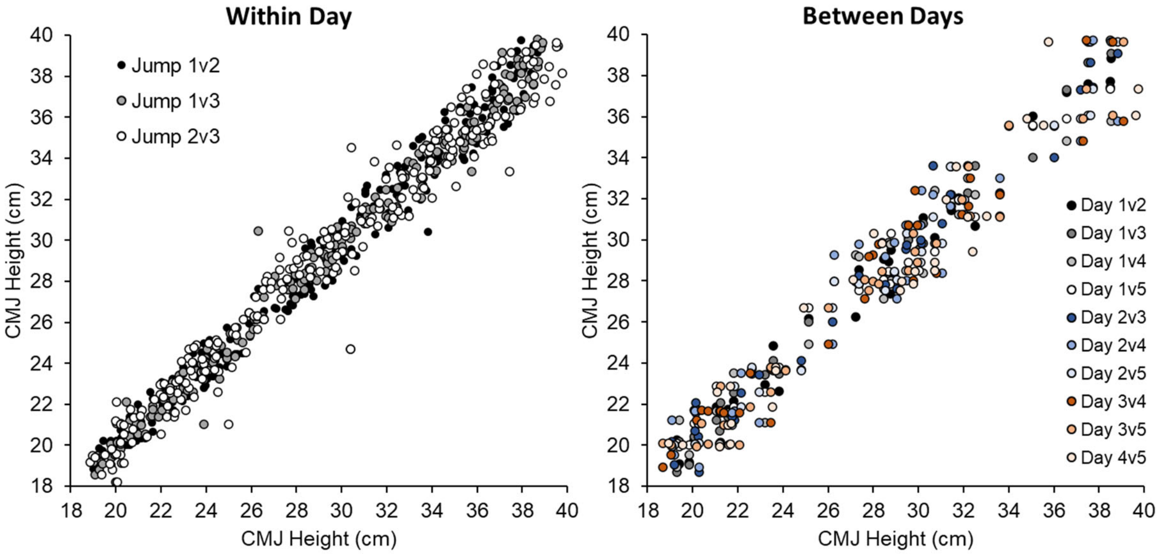


Figure 4.8. *Comparison of CMJ heights recorded Within and Between Days.*

Jump 1 (cm)	**Jump 2 (cm)**	**Jump 3 (cm)**	**ICC**	**CV (%)**
29.390 ± 0.382	29.329 ± 0.389	29.313 ± 0.385	0.987	1.938 ± 0.082

Values are means ± SEM.

Table 4.3. *CMJ Heights, ICC and CV values for the three jumps performed on the same day*

Between Day Consistency. Likewise, consistency of peak jump height across days was very good. Pearson correlations between individual days ranged from 0.955 to 0.986. Mean CMJ height, ICC and CV values are shown in Table 4.4.

Day 1 (cm)	**Day 2 (cm)**	**Day 3 (cm)**	**Day 4 (cm)**	**Day 5 (cm)**	**ICC**	**CV (%)**
27.660 ± 1.045	27.715 ± 1.065	27.803 ± 1.055	27.932 ± 1.036	27.586 ± 0.018	0.979	2.972 ± 0.140

Values are means ± SEM.

Table 4.4. *Peak CMJ Heights, ICC and CV values for the three jumps performed on five separate days.*

Study 2: Application

CMJ Height Changes During Training. The effects of a single day of training on individual CMJ height is shown in Figure 4.9. The mean reduction was 11.71cm ± 1.23% (30.50 ± 0.61 vs 27.14 ± 0.59 cm, $p<.05$).

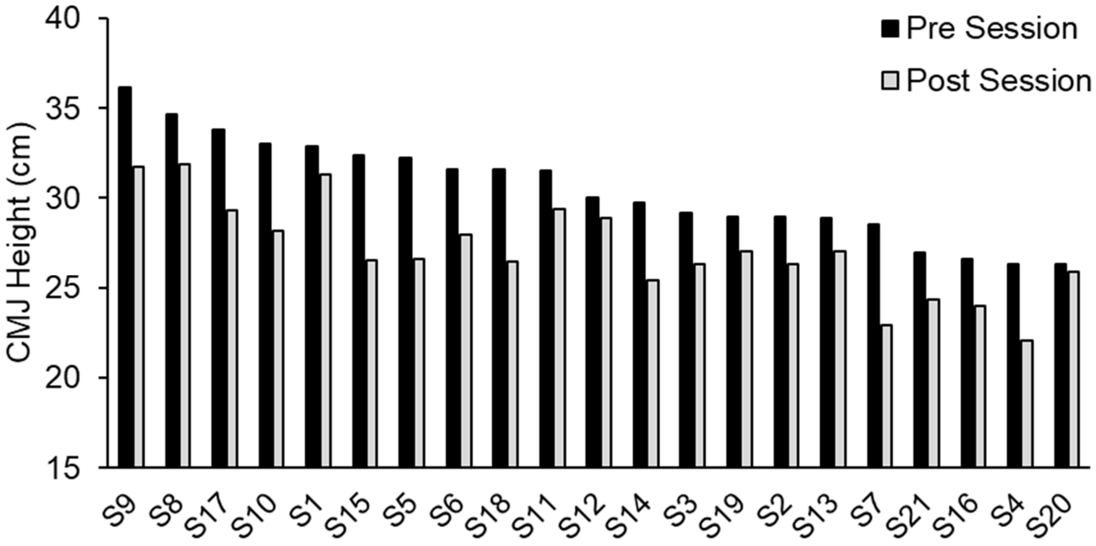


Figure 4.9. *CMJ heights for individual subjects recorded before and after a single training session.*

This session resulted in the players covering 9784.9 ± 152.8 m of total distance and 1206.1 ± 52.8 m or HML distance. There was a strong relationship between physical demands and CMJ height change (Figure 4.10). The Person correlation between relative CMJ height change, total distance and HML distance were -0.727 and -0.663.

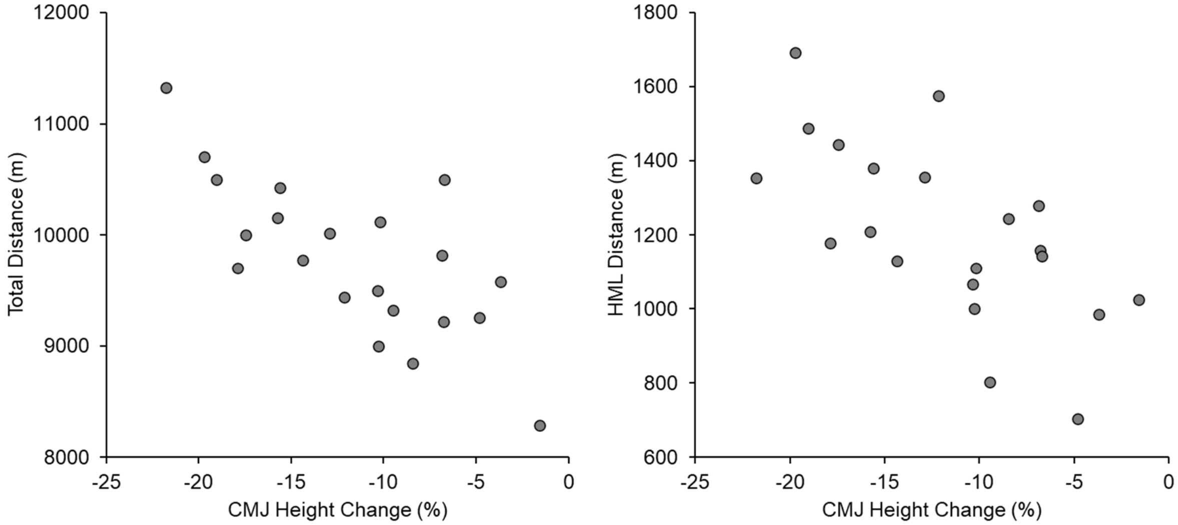


Figure 4.10. *Relationships between Total distance and HML distance performed during a single training session versus the relative change in CMJ height.*

CMJ Height Changes Across Training Days. Training loads for five of the six training days are shown in Table 4.5. The load for Day 6 is not shown as this data was collected after the subjects executed their CMJ for that day. The highest training loads (greatest total and HML distances) occurred on Days 1, 3 and 4 with the lowest loads on days 2 and 5.

Variable	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**
Total Distance (m)	8294.85 ± 205.80 ^{a}	8707.38 ± 241.80 ^{a}	4132.48 ± 124.85 ^{b}	8605.93 ± 206.17 ^{a}	2877.12 ± 76.30 ^{c}
HML Distance (m)	1646.97 ± 214.51 ^{a}	611.07 ± 163.63 ^{b}	226.59 ± 45.75 ^{c}	1895.89 ± 213.76 ^{a}	70.91 ± 19.33 ^{c}

Values are means ± SEM. Values with same letter are not significantly different ($p<.05$)

Table 4.5. Physical demands for the first five days of the training period.

CMJ heights measured each day across the 6-day evaluation period are shown in Figure 4.11. Compared to day 1, CMJ heights were significantly reduced on Days 2 and 5. In general, CMJ heights tended to be reduced following high training load days, where both total and HML distances were elevated. In particular, following Days 1 and 4, CMJ height was reduced by 8.5 and 11.3% on days 2 and 5.

Figure 4.11 also shows the recovery scores each day. In general, these scores show poorer perceptual readiness (higher scores) on the days following high training load days. For example, Day 2 recovery score was increased following Day 1 training. Also, higher recovery scores were associated with lower CMJ height.

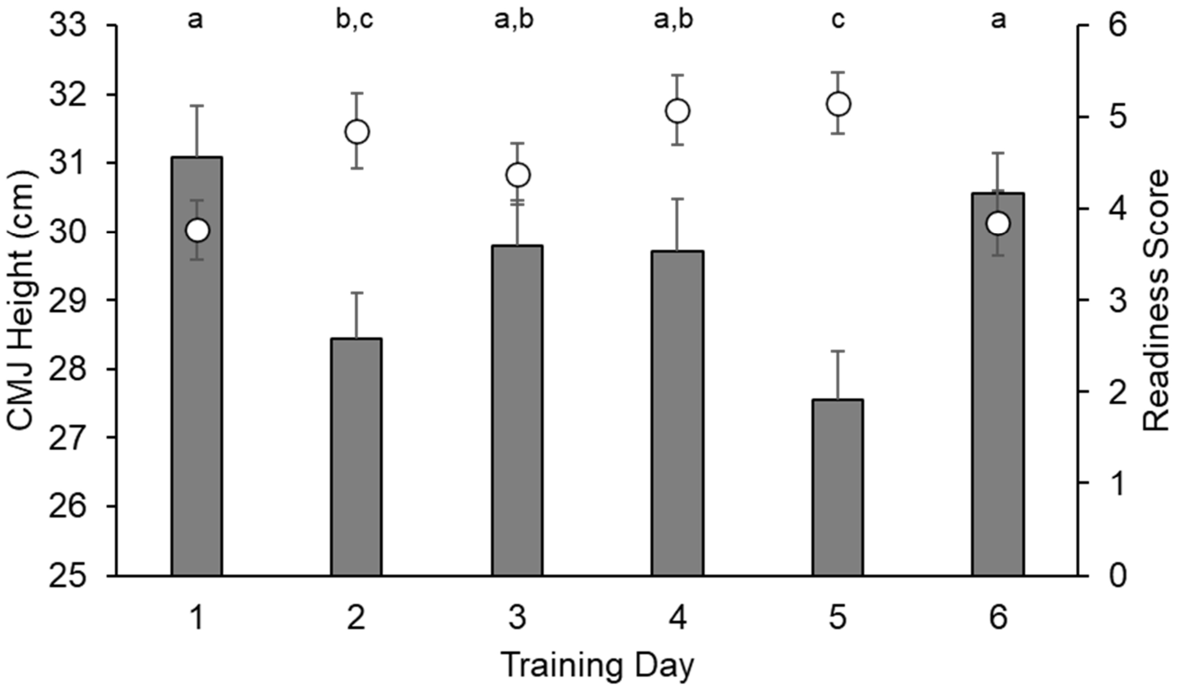


Figure 4.11. Peak CMJ height recorded across training days (bars). Days 1-5 represent Monday-Friday (consecutive) and Day 6 represents the following Monday (after two off-days). Bars with the same letter are not significantly different. For comparison, readiness scores for each day are also shown (symbols). Values are means ± SEM.

To understand how repeated training sessions affect CMJ height, training loads for Days 1 - 4 were summed. These accumulated load metrics were then compared to the relative change in CMJ height from Day 1 to Day 5 (the Day 5 load was excluded from this analysis as training after CMJ protocol was performed). The relationships between the accumulated total, HML distances and CMJ height change are shown in Figure 4.12. This figure shows that players who experienced greater training loads had the largest decrease in CMJ height. For accumulated total and HML distances, the correlation coefficients were, -0.813 and -0.789.

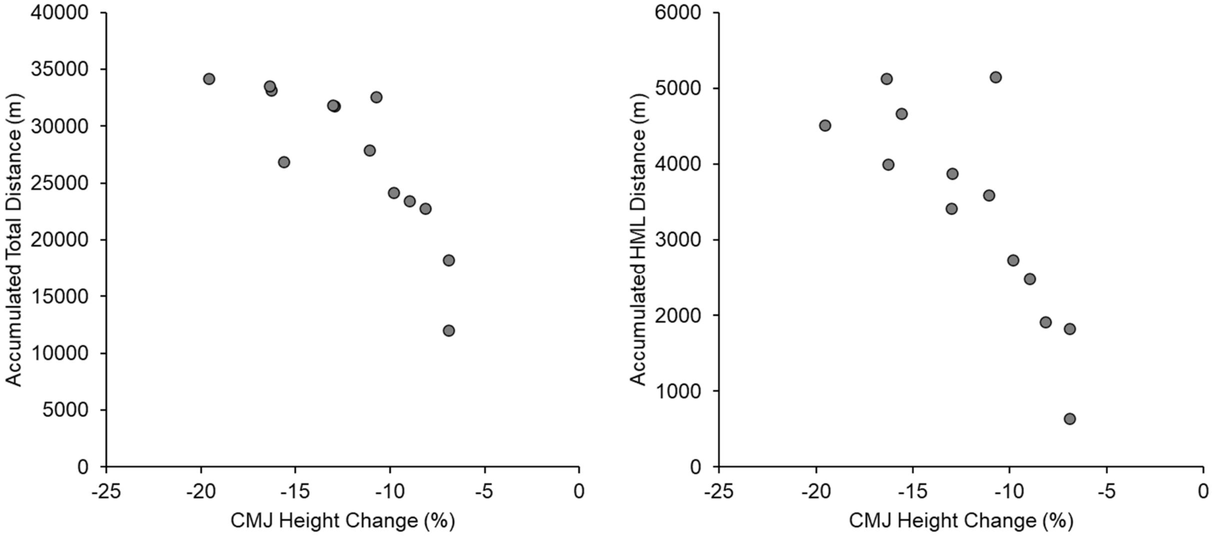


Figure 4.12. Relationships between accumulated total and HML distances and the relative change in CMJ height.

CMJ Height Changes During a Match. The physical demands (match loads) for the three groups are show in Table 4.6. Full-Time players covered more total and HML distance that the Part-Time and Reserve players while the Part-Time player experienced greater loads than the Reserves. Distances covered by the reserves reflect movements along the sidelines during the match as players are often asked to “keep warm” by periodically jogging and doing several short, moderate speed sprints.

Group	n	Total Distance (m)	HML Distance (m)

Full-Time	26	9789.85 ± 146.16 ^{a}	1439.26 ± 65.79 ^{a}
Part-Time	69	6430.94 ± 164.80 ^{b}	890.34 ± 32.62 ^{b}
Reserves	45	1041.76 ± 36.54 ^{c}	5.34 ± 51.51 ^{c}

Table 4.6. Total and HML distances covered by the three groups of players during a match.

Analysis of variance showed significant group x time interactions. Pre-Match CMJ heights were not significantly different between groups. However, there were post-match differences. Post-match CMJ heights were significantly lower in the Full-Time group that in the other two. Also, post-match CMJ height was significantly lower in the Part-Time groups compared to the reserves. This is shown in the left panel of Figure 4.13. The right panel of Figure 4.13 shows the relative changes in CMJ height within the three groups. There were larger reductions in the Full-Time group compared to the others and a larger reduction in the Part-Time group than the reserves.

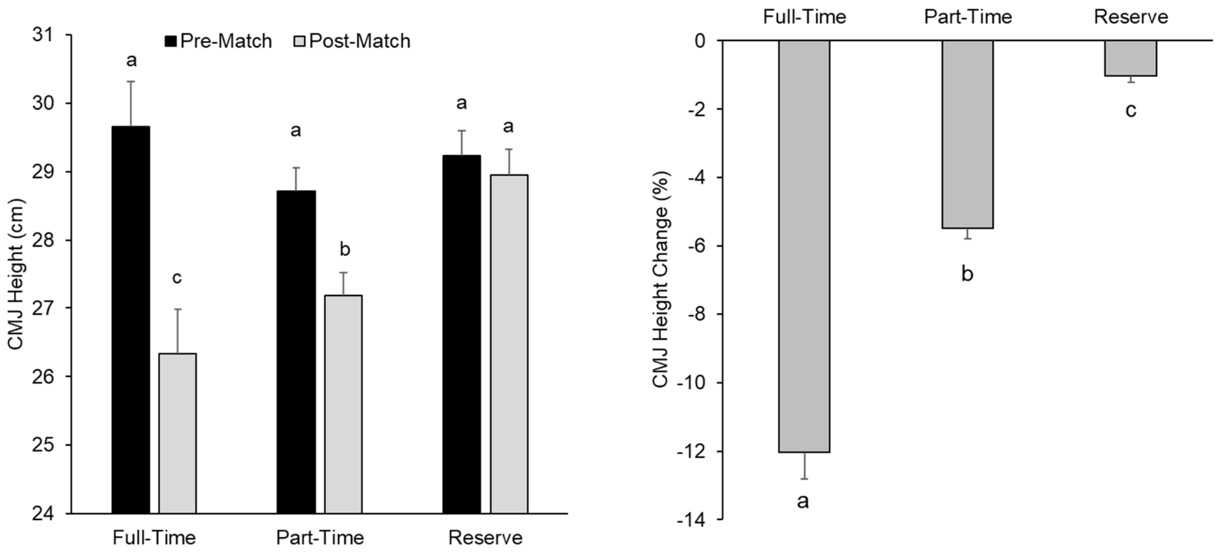


Figure 4.13. *Left:* CMJ heights recorded before and after competitive matches in the three groups of players. The asterisks indicate significant difference between pre- and post-match. *Right:* Relative decreases in post-match CMJ height. Bars with the same letter are not significantly different.

The relationships between total and HML distances and the relative change in CMJ height are shown in Figure 4.14. These data indicate that, regardless of group, players who experienced greater match loads also experienced the greater reductions in CMJ height. The correlation coefficient between total distance and the CMJ height change was -0.813 and HML distance and CMJ height change was -0.823.

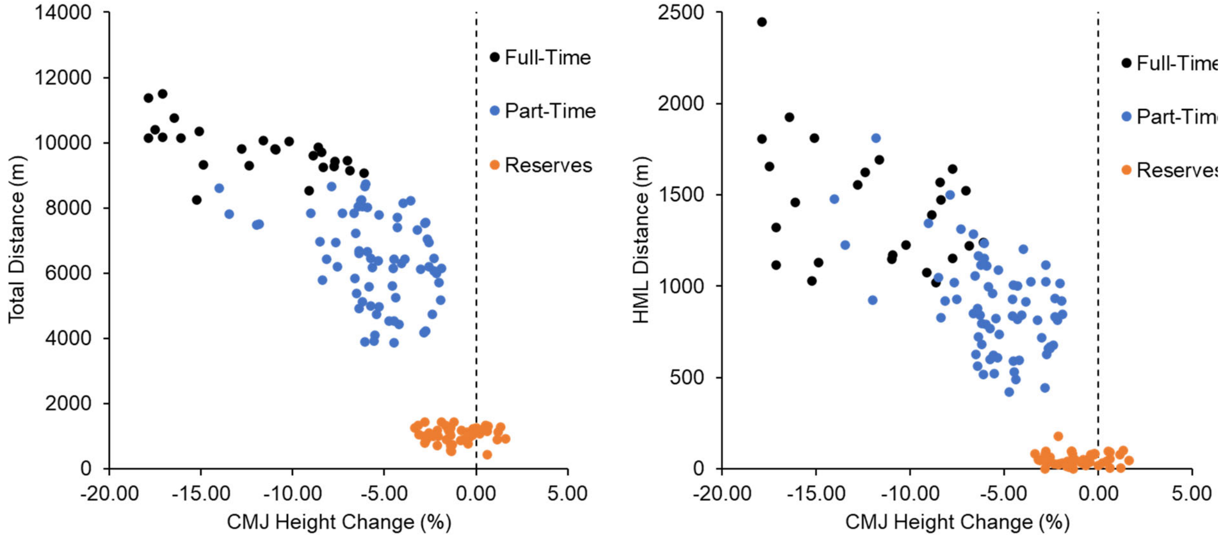


Figure 4.14. Relationships between total and HML distance versus the relative change in CMJ height for the three groups of players.

DISCUSSION

In the Literature Review, three questions were posed. First, are measurements of CMJ height using a trunk-mounted, GPS embedded, accelerometer reliable? Second, can a protocol for making those measurements be applied to a large group of players, on a regular basis? And third, do changes in CMJ height before and after training and/or matches reflective of the physical demands experience by the player? Based on the current results, the answers to these questions appear to be yes.

Consistency. The results show that vertical jump height can be reliably determined using the STATSports APEX IMU. As shown in Figure 4.8 (left panel), CMJ heights measured for the jumps during the three-jump protocol (within day) are highly correlated. Both Person correlation and intraclass correlation values were very high. In addition, the mean coefficient of variation for the jumps was less than 2%. In fact, only five sets of jumps had a CV above 5%. Figure 4.8 indicates that withing the 240 sets of jumps performed, there were several outliers. When these occurred, the CMJ heights were consistently lower than the other two. In no case was an "outlier jump" the subject's peak CMJ height. For example, the largest case of an outlier occurred during a series of jumps with CMJ heights of 30.39, 30.40 and 24.68 cm. By using the peak CMJ height values of the set of jumps, one can reliably gauge the peak performance of the athlete.

Day-to-day consistency was also found to be very good. For example, five days of testing under similar conditions (i.e. following two days or rest) also showed high Pearson and intraclass correlation coefficients of 0.95 or better. In addition, mean CV was less than 3%. In fact, the largest CV value for the 32 players was 4.3%. For this aspect of the study, peak CMJ height within the three-jump protocol was used. This was based on the within-day reliability discussed above.

It is important to note that the measurements made during this study were part of regular training sessions and matches. They had been performing the jump protocol as part of their daily warm up for several months. As such, the players were experienced and well versed in the protocol at the time of data collection. This may account for the high reliability measures found here.

In a recent systematic review, Clemente et al., argue that measuring CMJ height using flight-time, derived from vertical acceleration is a reliable measure.[44] For example, Rantalienen et al. also found good between-day reliability of CMJ heights measured using IMUs.[1] For their study, CMJ height was calculated using flight time (as was done in the present study). They report a CV, of 7.4%. Pearson and intraclass correlations were 0.969 and 0.959, respectively. While their mean CV is somewhat higher than reported here, the correlations are very similar. Nuzzo et al.[29] also found very good day-to-day reliability of the Myotest device (an IMU). Buchheit et al. was a similar study examining the reliability of field-based running-specific measures using a GPS-embedded accelerometer found similar conclusions as the accelerometers show acceptable levels of reliability.[35] Accordingly, the present study supports the use of IMUs to measure CMJ heights and extends the reliability concept to using the STATSports APEX device.

Applicability. The three-jump protocol was used with a large group of collegiate, female soccer players. The testing protocol was incorporated as part of the warm-up prior to the start of each match and training session. In some cases, it was also included at the end of the day's activity, preceding their cool down. As all players routinely wear the STATSports APEX device as part of the team athlete monitoring program, the protocol could be administered to all players, simultaneously. The protocol required less that 60 seconds to administer and players were continuously instructed as to readying themselves prior to the jump and encouraging them to give a maximal effort. There were no issues encountered using this simultaneous application. Players readily performed the three jumps and came to see it as a part of their regular warm-up routine. The coaching staff were also receptive to the protocol as it required minimal time away from other practice activities. Thus, given the reliability of the test and acceptance by the athletes, it is certainly applicable to a female, collegiate soccer team.

Applicability and sensitivity also refer to a tests ability to provide meaningful results and to characterize known conditions.[36,39,40,44] This can also be referred to as responsiveness and feasibility. The three-jump task presented here is capable of detecting decrements for acute and long-term effects of seven days of training on muscular performance resulting from fatigue and inadequate recovery. This is supported by within and between-day reductions in CMJ height following training and match play. Also, there were negative correlations between CMJ height decrements and markers of training load. As total and HML distances increased, CMJ heights declined. For the matches, pre-post reductions in CMJ height were greatest for those who played the largest number of minutes (Full-Time players) compared to Part-time players and players who did not play (Reserves). Thus, this method and protocol can be easily applied to a large number of athletes, requiring minimal training time, and used on a regular basis to monitor both short- and long-term fatigue. Further, the protocol is able to detect changes in performance expected to occur as the results of training and playing competitive matches. A study by Andersson et al. helps to support the decrease in vertical jump height the days following a match as their research indicated reductions in CMJ height up to 72 hours after a match.[7] It is also shown in a study by Sausaman that the differences in physical demands for collegiate level soccer are identified between playing positions, especially as total distance and the time of high speed running increases.[8] Another study by Nedelec et al. supports this correlation as their results showed that there was a significant relationship between the decrement in CMJ performance at 24 hours and the number of hard changes in direction performed during a match.[11] Conversely, Malone et al. found that CMJ performance was not significantly affected across an in-season microcycle after performing a CMJ test before and after 4 consecutive soccer training sessions of an in-season weekly microcycle.[14]

CMJ heights measured prior to training were also related to perceptual ratings of recovery. Across a week of training, poor recovery scores were reflected in reduced CMJ height on that day. Thus, CMJ heights measured here are indicative of player recovery and readiness for the day's session.

The vertical jump test is characterized by high practicality and low physiological strain.[15] The loss of jump height is an important indicator of acute and fatigue persisting over a long period, such as days to weeks.[7,15,16,22] The ability to monitor vertical jump in a large group of players, on a regular basis over the course of a soccer season is important in understanding the long-term impact of training and match loads. Fatigue resulting from overtraining is considered a risk factor for neuromuscular injury and likely affects match performances.[4] Thus, it is important to apply the proper training stimulus to maximize performance while minimizing injury risk. Claudino et al. found that adjusting training load based on pre-workout jump height resulted in decreased training loads without decreasing improvements in performance.[25] Thus, it seems reasonable to suggest that the three-jump protocol used here could be incorporated as an important component of an athlete monitoring and periodization program.

Soccer match activities have been shown to impact vertical jump performance. Several groups note that squat and countermovement jump heights are reduced at half-time and following competitive and simulated matches.[7,10,11] For example, de Hoya et al. report that CMJ height was significantly decreased at 30 minutes, 24, and 48 hours post-match.[46] On the other hand, Krustrup et al. showed no change in CMJ height after competitive matches.[47] Likewise, Faude et al. saw no change in CMJ height during a professional season.[48] However, individual subject decrements in performance were correlated with perceived stress scores.

Using changes in vertical jump height as a measure of fatigue does not indicate the underlying cause of the decreased performance. Fatigue (manifested as a decrease in jump height) involves both muscular and neural components. In this study, the perception of recovery was impaired indicating the potential for central fatigue. Others show reduced voluntary muscle activation associated with CMJ height.[10,12] Nedelec et al. also showed elevated markers of muscle damage that were associated with reduced performance in the days following a soccer match.[11] Thus, decreased CMJ height shown in this study over the course of several days likely reflects both muscle damage as well as reduced central drive. Clearly, this is an issue that warrants more study.

There were important limitations to this study. Since the data was collected during normal soccer settings for both training and matches, we could not measure nor control the subjects' sleep, diet, and external stressor (academics, social life, etc.). Additionally, extra physical activities subjects may have engaged in were also not measured nor controlled. There was also a short between-jump time intervals may not have allowed athletes to adequately prepare for the subsequent jump. In fact, it was noticeable when a single jump varied greatly compared to the other two. Despite this, the ICC and CV within trials were quite good. In addition, the CMJ height of the three jumps was quite consistent across days. Nevertheless, providing additional time between jumps may improve inter-jump reliability without imposing an unreasonable time burden. Another major limitation was noticed as these jumps are maximal, voluntary efforts and performed as a group, there is the possibility that motivation affected the jump height. While players were encouraged daily to give their best effort, we have no direct measure of an individual player's effort level. The CV of jumps performed on a single day were small, suggesting a high sincerity of effort. However, it should be noted that use of the CVs as an indicator of true maximal effort is not universally accepted.[49] Lastly, we did not perform detailed analysis of acceleration and deceleration during each jump. Some have shown an additional time-motion characteristic so the jump may be more sensitive to the effect of fatigue than CMJ height.

CONCLUSIONS

The overall goal of this project was to assess if countermovement jump is a feasible way to measure player fatigue and readiness in female soccer players. The results indicate that the three-jump protocol and the use of a trunk-mounted accelerometer provide reliable measures of CMJ height. In addition, the approach can be easily applied to a large group of athletes within a very short time frame. Also, the data generated by the CMJs are responsive to detect the fatiguing effects of soccer activity. Thus, this approach can be used confidently as a measure of athlete neuromuscular performance, fatigue, and readiness. Future work should focus on other aspects of the jump that might provide additional performance information. For example, power output generated during the jump, the concentric and eccentric phases of the jump, and trunk rotations during the landing phase may provide information on performance changes was well as the biomechanics of jumping and landing. For example, Williams et al. showed that athletes with prior anterior cruciate ligament tears show different trunk rotation kinematics during landing that those without injury.[42] While the protocol used here and the data generated appear to be useful in athlete monitoring, it remains to be see as to other applications of the jump protocol and wearable technology.

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APPENDIX

Table A1. Subject characteristics and a list of subjects participating in each aspect of the study.

				Reliability Study		Applicability Study		
Subject	**Age**	**Height**	**Weight**	**Day**	**Week**	**Training Day**	**Training Week**	**Match**
DH-003	19	165.10	51.33					X
DH-030	22	162.56	52.31	X	X	X	X	
DH-009	22	175.26	53.26		X			X
DH-020	22	162.56	53.88	X	X	X		X
DH-031	20	167.64	57.23	X	X			
DH-011	23	175.26	57.69	X	X			X
DH-010	21	162.56	58.68		X			X
DH-022	23	172.33	59.41	X	X	X		X
DH-002	22	162.56	59.95					X
DH-032	18	167.64	60.68	X	X			
DH-014	18	160.02	61.32	X	X			X
DH-027	20	170.18	61.41	X	X	X		X
DH-021	18	170.18	62.35	X	X	X		X
DH-036	19	162.89	63.04	X	X	X	X	
DH-013	23	170.18	63.40	X	X			X
DH-016	18	165.10	63.58	X	X			X
DH-026	19	167.64	64.76	X	X	X		X
DH-006	22	160.02	64.85					X
DH-038	22	174.90	65.11	X	X	X	X	
DH-015	18	175.26	65.67	X	X			X
DH-034	22	163.83	65.93	X	X	X	X	
DH-024	22	175.26	66.39	X	X	X	X	X
DH-019	20	167.64	66.54	X	X	X		X
DH-028	18	175.26	67.66	X	X	X	X	X
DH-035	18	170.73	68.49	X	X	X	X	
DH-039	21	162.76	68.55	X	X	X	X	
DH-008	20	177.80	68.75					X
DH-040	19	170.91	70.42	X	X	X	X	
DH-037	21	173.93	70.90	X	X	X	X	
DH-007	21	180.34	71.47					X
DH-005	20	172.72	71.93					X
DH-033	19	162.83	72.92	X	X	X	X	
DH-018	19	170.18	72.93	X	X	X		X
DH-029	19	177.80	74.38	X	X			
DH-001	21	170.18	76.37					X
DH-012	19	170.18	78.55	X	X			X
DH-023	22	170.67	78.91	X	X	X	X	X
DH-017	22	175.26	81.90	X	X			X
DH-004	20	177.80	84.72					X
DH-025	18	175.26	89.71	X	X	X	X	X

Table A2. Raw data used to calculate within-day reliability. CMJ values are in cm.

Measure	Day	Subject	CMJ1	CMJ2	CMJ3
1	1	1	19.01	18.85	19.16
2	2	1	19.08	19.38	18.56
3	3	1	19.18	18.98	19.51
4	4	1	19.26	19.85	18.82
5	5	1	19.41	19.72	19.07
6	6	1	19.43	20.21	19.52
7	7	1	19.77	20.21	20.06
8	8	1	19.82	19.07	19.40
9	1	2	19.95	19.53	19.55
10	2	2	19.99	20.08	18.20
11	3	2	20.02	20.22	21.06
12	4	2	20.04	20.04	19.59
13	5	2	20.06	20.20	20.15
14	6	2	20.21	20.73	20.15
15	7	2	20.23	19.79	19.82
16	8	2	20.26	20.37	19.12
17	1	3	20.48	20.01	22.13
18	2	3	20.52	20.54	20.87
19	3	3	20.62	21.38	20.40
20	4	3	20.63	20.00	21.19
21	5	3	20.74	20.77	20.80
22	6	3	20.89	20.80	21.33
23	7	3	20.92	20.22	21.04
24	8	3	20.98	22.01	20.53
25	1	4	21.12	21.14	21.72
26	2	4	21.13	20.35	20.98
27	3	4	21.32	20.36	20.56
28	4	4	21.52	22.59	21.40
29	5	4	21.58	21.09	21.41
30	6	4	21.63	22.29	21.90
31	7	4	21.65	20.67	21.76
32	8	4	21.88	22.24	21.37
33	1	5	22.04	23.08	21.70
34	2	5	22.09	21.97	22.49
35	3	5	22.12	22.87	22.23
36	4	5	22.36	21.95	22.95
37	5	5	22.37	22.73	22.55
38	6	5	22.41	22.41	22.58
39	7	5	22.50	22.10	22.38
40	8	5	22.51	23.24	22.82
41	1	6	22.53	22.64	23.10
42	2	6	22.53	22.63	21.60
43	3	6	22.55	21.70	22.23
44	4	6	22.82	23.43	23.42
45	5	6	22.94	22.15	22.99
46	6	6	22.98	23.47	22.36
47	7	6	23.00	23.80	23.57
48	8	6	23.00	22.40	22.79
49	1	7	23.05	23.08	23.03
50	2	7	23.17	22.40	22.68
51	3	7	23.41	24.51	22.59
52	4	7	23.53	23.92	23.61
53	5	7	23.58	23.32	23.66
54	6	7	23.77	23.91	23.99
55	7	7	23.79	24.55	23.61
56	8	7	23.83	24.08	23.65

57	1	8	23.90	24.99	21.03
58	2	8	23.90	22.81	23.19
59	3	8	23.92	23.96	23.61
60	4	8	23.98	23.20	24.26
61	5	8	23.98	22.93	24.09
62	6	8	23.99	23.44	24.03
63	7	8	24.03	24.37	23.70
64	8	8	24.03	23.25	24.70
65	1	9	24.14	25.15	23.82
66	2	9	24.28	23.38	24.05
67	3	9	24.30	23.58	24.89
68	4	9	24.42	24.12	24.99
69	5	9	24.51	23.47	24.79
70	6	9	24.59	23.83	23.25
71	7	9	24.67	24.44	24.86
72	8	9	24.92	23.83	24.19
73	1	10	24.92	24.38	24.24
74	2	10	24.93	25.75	24.54
75	3	10	25.06	25.16	25.45
76	4	10	25.27	24.46	24.34
77	5	10	25.37	25.27	25.76
78	6	10	25.39	24.44	25.13
79	7	10	25.63	24.51	25.01
80	8	10	25.91	25.92	26.47
81	1	11	25.94	25.32	25.39
82	2	11	26.07	26.26	25.65
83	3	11	26.13	27.29	26.14
84	4	11	26.24	25.67	26.16
85	5	11	26.31	26.14	26.30
86	6	11	26.49	26.26	26.29
87	7	11	26.56	26.18	27.22
88	8	11	26.58	26.56	26.15
89	1	12	27.06	26.69	28.24
90	2	12	27.10	26.68	27.82
91	3	12	27.50	26.63	27.98
92	4	12	27.62	26.54	27.60
93	5	12	27.73	26.89	27.95
94	6	12	27.83	28.59	28.55
95	7	12	27.83	26.84	27.66
96	8	12	27.85	27.27	28.55
97	1	13	27.94	27.32	27.16
98	2	13	27.95	28.13	28.30
99	3	13	28.22	27.34	27.92
100	4	13	28.36	27.39	27.58
101	5	13	28.36	27.59	28.08
102	6	13	28.41	29.62	28.41
103	7	13	28.58	27.70	28.58
104	8	13	28.58	27.89	28.64
105	1	14	28.64	29.88	29.43
106	2	14	28.65	27.60	28.10
107	3	14	28.67	29.74	28.68
108	4	14	28.68	28.61	28.20
109	5	14	28.74	27.26	29.17
110	6	14	28.90	29.33	28.06
111	7	14	29.04	30.02	29.44
112	8	14	29.23	29.76	29.24
113	1	15	29.24	30.46	29.34
114	2	15	29.27	27.81	29.89
115	3	15	29.29	29.03	28.46

116	4	15	29.37	28.08	28.90
117	5	15	29.41	28.30	29.19
118	6	15	29.50	29.81	30.18
119	7	15	29.52	28.31	30.11
120	8	15	29.56	28.46	29.27
121	1	16	29.59	28.02	29.04
122	2	16	29.74	29.48	29.78
123	3	16	29.80	30.17	30.66
124	4	16	29.81	30.59	28.52
125	5	16	26.32	27.65	30.47
126	6	16	29.94	30.16	30.23
127	7	16	29.99	29.21	29.97
128	8	16	30.02	30.94	29.70
129	1	17	30.10	29.02	29.46
130	2	17	30.38	29.36	30.11
131	3	17	30.39	30.40	24.68
132	4	17	30.40	30.15	30.38
133	5	17	30.42	31.62	30.70
134	6	17	30.44	29.57	30.52
135	7	17	30.66	29.23	30.42
136	8	17	30.84	31.23	31.03
137	1	18	31.01	31.12	30.80
138	2	18	31.05	32.42	31.63
139	3	18	31.06	32.29	31.12
140	4	18	31.12	32.66	31.23
141	5	18	31.18	30.90	31.50
142	6	18	31.22	30.87	30.94
143	7	18	31.43	31.66	31.56
144	8	18	31.48	30.29	32.09
145	1	19	31.63	31.67	31.84
146	2	19	31.73	32.45	31.54
147	3	19	31.97	32.98	31.17
148	4	19	31.97	33.18	32.48
149	5	19	32.06	30.62	31.82
150	6	19	32.07	31.36	31.11
151	7	19	32.23	31.28	30.88
152	8	19	32.26	32.50	31.43
153	1	20	32.45	32.25	31.63
154	2	20	32.47	33.63	32.55
155	3	20	32.58	33.31	32.10
156	4	20	32.58	32.65	32.07
157	5	20	32.81	32.66	33.24
158	6	20	33.81	30.43	34.53
159	7	20	32.82	33.59	33.06
160	8	20	32.96	31.46	33.85
161	1	21	33.17	34.60	33.74
162	2	21	33.31	32.11	33.55
163	3	21	33.44	34.92	34.25
164	4	21	33.48	31.98	33.01
165	5	21	33.53	34.03	32.07
166	6	21	33.56	35.06	32.64
167	7	21	33.62	32.71	33.03
168	8	21	33.74	32.44	34.65
169	1	22	33.87	33.60	34.48
170	2	22	33.90	34.03	33.79
171	3	22	33.96	34.66	33.71
172	4	22	34.12	33.20	33.31
173	5	22	34.19	33.91	33.38
174	6	22	34.23	33.85	34.32

175	7	22	34.26	34.16	34.88
176	8	22	34.33	34.27	35.20
177	1	23	34.48	34.07	35.26
178	2	23	34.57	36.27	34.70
179	3	23	34.60	35.86	34.10
180	4	23	34.63	35.26	34.79
181	5	23	34.69	34.81	34.10
182	6	23	34.71	34.63	35.43
183	7	23	34.89	33.93	33.87
184	8	23	35.24	36.50	34.85
185	1	24	35.35	34.06	35.24
186	2	24	35.39	34.79	34.58
187	3	24	35.41	34.91	34.41
188	4	24	35.41	35.23	36.29
189	5	24	35.44	33.92	34.52
190	6	24	35.45	34.88	34.78
191	7	24	35.51	35.79	35.12
192	8	24	35.56	34.83	36.49
193	1	25	35.66	36.57	35.62
194	2	25	35.69	36.63	35.01
195	3	25	35.70	36.18	35.50
196	4	25	35.72	35.00	35.74
197	5	25	35.75	37.45	33.34
198	6	25	35.80	36.67	34.85
199	7	25	35.80	35.48	35.37
200	8	25	35.82	34.23	35.36
201	1	26	35.88	36.61	35.78
202	2	26	35.98	34.74	35.01
203	3	26	36.24	35.98	35.35
204	4	26	36.36	36.49	35.59
205	5	26	36.41	35.31	36.98
206	6	26	36.66	37.43	36.01
207	7	26	36.67	37.26	36.06
208	8	26	36.67	37.94	36.49
209	1	27	36.72	36.84	36.06
210	2	27	36.76	36.01	36.32
211	3	27	36.88	38.50	36.68
212	4	27	36.98	36.78	37.64
213	5	27	37.09	37.52	39.16
214	6	27	37.18	35.54	37.37
215	7	27	37.19	36.37	37.15
216	8	27	37.26	35.96	38.10
217	1	28	37.38	35.69	36.80
218	2	28	37.40	37.01	36.91
219	3	28	37.47	38.55	38.04
220	4	28	37.62	37.90	36.39
221	5	28	37.77	36.28	38.60
222	6	28	37.78	39.22	36.78
223	7	28	37.80	38.21	38.84
224	8	28	37.85	36.74	38.52
225	1	29	37.95	39.77	38.13
226	2	29	38.05	37.13	38.76
227	3	29	38.06	38.36	38.56
228	4	29	38.12	38.59	36.98
229	5	29	38.32	38.96	37.87
230	6	29	38.39	38.16	39.20
231	7	29	38.50	39.48	37.59
232	8	29	38.51	37.99	37.61
233	1	30	38.57	38.59	39.50

234	2	30	38.64	39.59	39.47
235	3	30	38.66	40.13	39.81
236	4	30	38.69	39.17	38.46
237	5	30	38.72	38.49	38.70
238	6	30	38.75	39.53	39.44
239	7	30	38.83	40.27	39.35
240	8	30	38.91	39.51	39.64

Table A3. Data used to asses between-day reliability.

Subject	Day 1	Day 2	Day 3	Day 4	Day 5
1	32.18	33.62	32.29	33.01	31.16
2	23.81	22.63	23.48	23.70	23.79
3	21.04	21.85	21.22	21.66	22.87
4	25.14	26.19	26.01	24.91	26.69
5	30.71	30.12	29.85	32.41	29.44
6	31.46	31.43	32.20	31.66	33.58
7	30.03	29.46	29.55	30.71	28.49
8	27.21	26.26	27.99	29.25	27.97
9	36.57	37.18	37.30	34.80	35.90
10	19.84	19.17	19.06	19.55	20.01
11	31.79	32.03	31.92	31.23	31.95
12	37.51	37.61	38.62	39.63	36.05
13	21.84	22.15	22.55	23.53	21.86
14	28.45	29.05	27.61	27.13	28.05
15	19.31	20.27	18.70	18.95	20.08
16	28.66	28.95	28.37	29.85	28.45
17	32.51	30.66	33.59	32.18	31.13
18	29.56	30.10	29.97	30.73	28.90
19	27.38	28.53	27.81	29.18	27.53
20	21.55	21.76	21.36	21.57	20.98
21	28.75	27.38	28.24	29.77	27.85
22	21.25	20.14	22.07	21.59	20.03
23	20.08	20.25	20.40	21.70	21.07
24	23.21	22.97	23.45	21.10	22.60
25	35.07	36.02	34.02	35.55	35.60
26	21.19	20.09	20.69	21.66	20.05
27	30.21	31.06	30.79	28.39	29.84
28	23.58	24.83	24.11	23.68	23.63
29	28.78	29.49	29.76	28.01	30.31
30	38.55	38.83	39.09	35.78	39.63
31	38.49	37.72	37.43	39.74	37.33
32	19.42	19.10	20.18	21.20	19.92

Table A4. CMJ Height data used for the training week evaluation.

	Mon	Tues	Wed	Thurs	Fri	Mon	Accumulated	
Player	**1**	**2**	**3**	**4**	**5**	**6**	**Tot Dist**	**HML Dist**
S1	32.87	30.02	29.88	29.65	27.01	31.99	34239.7	4514.7
S2	28.97	27.06	27.52	27.06	26.02	29.41	32589.4	5152.0
S3	29.17	27.52	30.14	26.00	26.10	29.31	27902.6	3592.2
S4	26.37	24.65	26.03	25.81	23.16	25.81	31778.4	3874.4
S5	32.26	30.99	30.32	34.28	30.1	32.17	11999.9	1823.6
S6	31.61	29.41	30.75	30.99	28.65	31.11	24164.4	2733.9
S7	28.52	26.99	25.70	28.22	24.22	28.15	33151.9	4000.4
S8	34.67	25.14	34.65	33.76	29.65	34.12	26923.5	4675.4
S9	36.12	32.93	32.36	33.16	33.02	32.49	23433.1	2488.3
S10	33.00	30.21	29.89	28.332	28.00	30.41	33542.8	5127.4
S11	31.50	29.5	29.89	28.58	27.65	30.50	31898.9	3414.2
S12	30.02	28.49	29.29	29.89	27.67	31.36	22796.2	1911.1
S13	28.93	26.93	30.87	30.50	27.00	30.38	18236.2	640.3

Table A5. Data used for the within session CMJ changes.

Player	Pre	Post	% Change	cm Change	Tot Dist	HML Dist
S9	36.12	31.74	-12.91	-4.38	10016	1355
S8	34.67	31.86	-8.45	-2.81	8847	1245
S17	33.84	29.31	-14.36	-4.53	9775	1129
S10	33	28.22	-15.62	-4.78	10429	1380
S1	32.87	31.32	-4.83	-1.55	9253	705
S15	32.36	26.55	-19.72	-5.81	10702	1691
S5	32.26	26.65	-19.05	-5.61	10501	1488
S6	31.61	27.99	-12.15	-3.62	9435	1575
S18	31.58	26.51	-17.46	-5.07	10004	1445
S11	31.5	29.41	-6.86	-2.09	9817	1281
S12	30.02	28.93	-3.70	-1.09	9576	985
S14	29.78	25.43	-15.75	-4.35	10155	1210
S3	29.17	26.32	-10.27	-2.85	9000	1000
S19	28.98	27.08	-6.78	-1.90	9218	1158
S2	28.97	26.35	-9.47	-2.62	9321	803
S13	28.93	27.05	-6.72	-1.88	10500	1143
S7	28.52	22.92	-21.77	-6.6	11325	1355
S21	26.97	24.35	-10.20	-2.62	10120	1110
S16	26.63	24.01	-10.34	-2.62	9498	1067
S4	26.37	22.04	-17.89	-4.33	9702	1178
S20	26.34	25.93	-1.58	-0.41	8291	1024

Table A6. Data used for the CMJ changes during a match.

Match	Player	Player-Match	Role	Pre	Post	VJ Change	Total Dist	HMLD
1	6	111	Full-Time	33.616	28.86	-15.24	8238.1	1027.3
2	6	112	Full-Time	33.77	30.83	-9.10	8534.4	1076.2
2	5	117	Full-Time	31.501	29.63	-6.11	9064.3	1238.2
3	5	118	Full-Time	25.662	23.96	-6.87	9134.1	1222.1
4	5	119	Full-Time	32.817	27.92	-16.11	10136.9	1458.2
5	5	120	Full-Time	28.01	25.77	-8.34	9238.6	1472.6
1	4	121	Full-Time	30.451	28.19	-7.73	9271.3	1643.8
2	4	122	Full-Time	27.402	24.21	-12.37	9295.5	1624.9
3	4	123	Full-Time	33.489	28.86	-14.86	9322.1	1131.7
4	4	124	Full-Time	32.526	30.11	-7.72	9428.3	1153.1
5	4	125	Full-Time	27.995	26.10	-7.02	9463.3	1521.7
1	3	126	Full-Time	31.533	28.86	-8.87	9602.6	1391.4
2	3	127	Full-Time	30.338	27.89	-8.41	9711.1	1568.3
3	3	128	Full-Time	27.852	24.97	-10.93	9788.1	1171.6
4	3	129	Full-Time	24.388	21.85	-10.98	9809.1	1146.7
5	3	130	Full-Time	28.604	25.17	-12.77	9820.4	1556.5
1	2	131	Full-Time	32.669	29.97	-8.63	9852.2	1018.7
2	2	132	Full-Time	33.642	30.38	-10.21	10045.4	1225.5
3	2	133	Full-Time	33.937	30.21	-11.63	10063.6	1694.7
4	2	134	Full-Time	25.065	20.95	-17.86	10137.3	2445.8
5	2	135	Full-Time	24.71	20.81	-17.12	10170.7	1115.7
1	1	136	Full-Time	25.328	21.77	-15.10	10360.3	1809.9
2	1	137	Full-Time	24.874	20.87	-17.49	10404.8	1655.4
3	1	138	Full-Time	29.741	25.22	-16.44	10770.0	1924.6
4	1	139	Full-Time	33.647	28.12	-17.89	11370.0	1805.2
5	1	140	Full-Time	27.624	23.27	-17.12	11504.0	1320.7
5	22	35	Part-Time	26.776	26.03	-2.84	4174.9	445.5
2	21	37	Part-Time	28.978	27.42	-5.51	4102.3	522.6
5	21	40	Part-Time	30.252	28.92	-4.50	4526.6	588.5
1	20	41	Part-Time	26.395	25.17	-4.75	4543.0	419.8
4	20	44	Part-Time	25.42	24.31	-4.46	3871.3	531.9
5	20	45	Part-Time	25.078	23.60	-6.09	3887.5	518.2
3	19	48	Part-Time	26.914	25.46	-5.55	3926.4	621.6
1	18	51	Part-Time	29.657	28.85	-2.75	4229.2	625.5
2	18	52	Part-Time	32.997	31.64	-4.20	4426.4	594.5
5	18	55	Part-Time	26.689	25.27	-5.45	4735.8	825.4
1	17	56	Part-Time	29.088	28.40	-2.38	4737.9	677.0
2	17	57	Part-Time	24.663	23.13	-6.39	4911.0	563.8
3	17	58	Part-Time	28.327	26.87	-5.28	4978.1	735.8
4	17	59	Part-Time	31.12	29.38	-5.75	4988.4	769.2
5	17	60	Part-Time	30.997	29.13	-6.21	5112.8	683.6
1	16	61	Part-Time	30.796	30.21	-1.93	5178.5	918.1
2	16	62	Part-Time	26.064	24.95	-4.38	5247.6	488.6
3	16	63	Part-Time	25.414	23.81	-6.52	5374.4	626.7
4	16	64	Part-Time	24.373	22.99	-5.82	5592.2	996.0
5	16	65	Part-Time	27.816	26.57	-4.57	5616.4	929.0
1	15	66	Part-Time	31.422	30.79	-2.03	5723.0	1014.1
2	15	67	Part-Time	33.489	30.80	-8.36	5779.4	827.0
3	15	68	Part-Time	33.824	31.66	-6.62	5838.6	849.5
4	15	69	Part-Time	27.542	26.95	-2.17	5994.1	815.8
5	15	70	Part-Time	25.466	24.89	-2.28	6072.0	934.5
1	14	71	Part-Time	25.818	25.05	-3.01	6118.1	717.0
2	14	72	Part-Time	25.093	24.62	-1.89	6136.0	846.8
3	14	73	Part-Time	32.992	31.53	-4.54	6152.4	837.3
4	14	74	Part-Time	26.751	25.28	-5.64	6181.8	960.0

5	14	75	Part-Time	31.514	30.71	-2.57	6191.0	669.2
1	13	76	Part-Time	26.985	25.02	-7.54	6197.7	930.3
2	13	77	Part-Time	25.929	24.89	-4.08	6299.3	842.8
3	13	78	Part-Time	28.926	27.42	-5.35	6371.3	609.7
4	13	79	Part-Time	33.342	31.88	-4.49	6439.8	1007.8
5	13	80	Part-Time	24.348	23.42	-3.87	6441.6	914.1
1	12	81	Part-Time	26.436	24.37	-8.14	6441.7	919.9
2	12	82	Part-Time	31.076	29.34	-5.76	6443.4	597.9
3	12	83	Part-Time	29.136	28.48	-2.29	6456.1	830.9
4	12	84	Part-Time	25.567	23.99	-6.36	6612.7	722.8
5	12	85	Part-Time	32.865	30.97	-5.95	6647.7	789.7
1	11	86	Part-Time	29.836	27.99	-6.37	6680.1	1165.0
2	11	87	Part-Time	30.191	27.96	-7.66	6939.8	1020.8
3	11	88	Part-Time	24.292	23.68	-2.56	6953.2	659.9
4	11	89	Part-Time	32.599	29.94	-8.52	6957.5	1045.7
5	11	90	Part-Time	31.107	30.29	-2.66	7056.9	660.5
1	10	91	Part-Time	27.647	25.89	-6.55	7222.4	1056.6
2	10	92	Part-Time	26.948	26.09	-3.23	7335.0	813.5
3	10	93	Part-Time	24.831	23.79	-4.28	7414.3	818.5
4	10	94	Part-Time	32.825	29.11	-11.99	7472.9	923.7
5	10	95	Part-Time	26.091	23.18	-11.82	7510.0	1812.6
1	9	96	Part-Time	33.942	33.01	-2.80	7533.2	1023.8
2	9	97	Part-Time	30.812	29.97	-2.76	7558.8	1116.4
3	9	98	Part-Time	24.388	23.37	-4.28	7718.8	1000.4
4	9	99	Part-Time	29.854	28.31	-5.30	7782.1	1090.3
5	9	100	Part-Time	27.327	23.88	-13.47	7813.5	1227.5
1	8	101	Part-Time	26.42	24.14	-9.01	7826.7	1346.2
2	8	102	Part-Time	30.576	28.42	-7.29	7829.3	1312.2
3	8	103	Part-Time	30.523	28.56	-6.63	7847.7	1285.4
4	8	104	Part-Time	32.573	30.70	-5.94	8012.1	1110.5
5	8	105	Part-Time	28.929	27.13	-6.41	8038.0	876.9
1	7	106	Part-Time	27.594	25.94	-6.19	8052.0	796.3
2	7	107	Part-Time	31.522	30.29	-3.97	8139.6	1203.0
3	7	108	Part-Time	32.607	30.62	-6.29	8222.1	839.5
4	7	109	Part-Time	29.698	28.66	-3.56	8234.1	1023.5
5	7	110	Part-Time	31.881	29.96	-6.23	8237.3	1117.0
3	6	113	Part-Time	25.808	22.43	-14.03	8596.6	1478.6
4	6	114	Part-Time	25.812	24.29	-6.07	8661.0	1235.1
5	6	115	Part-Time	27.923	25.80	-7.89	8668.1	1502.2
1	5	116	Part-Time	30.017	28.26	-6.04	8724.2	1153.3
1	28	1	Reserve	25.695	25.57	-0.49	817.9	54.8
2	28	2	Reserve	33.197	32.97	-0.68	886.0	19.7
3	28	3	Reserve	31.71	30.83	-2.83	989.5	79.8
4	28	4	Reserve	26.465	26.10	-1.37	1015.1	81.7
5	28	5	Reserve	27.38	27.83	1.63	911.3	45.5
1	27	6	Reserve	33.515	33.05	-1.39	557.2	94.4
2	27	7	Reserve	30.639	30.52	-0.40	954.6	76.4
3	27	8	Reserve	31.158	31.35	0.61	423.5	56.7
4	27	9	Reserve	28.89	28.11	-2.73	895.5	25.2
5	27	10	Reserve	27.726	27.28	-1.63	904.8	40.5
1	26	11	Reserve	30.241	30.61	1.21	1119.1	4.8
2	26	12	Reserve	29.623	29.56	-0.22	1021.8	77.4
3	26	13	Reserve	33.312	32.88	-1.31	743.6	0.5
4	26	14	Reserve	28.577	28.17	-1.43	1108.6	95.5
5	26	15	Reserve	26.994	26.37	-2.33	1008.9	27.8
1	25	16	Reserve	29.425	29.19	-0.80	1175.4	48.1
2	25	17	Reserve	25.508	24.86	-2.57	1092.1	66.3
3	25	18	Reserve	25.545	25.16	-1.53	1198.7	10.1
4	25	19	Reserve	29.846	29.43	-1.39	1254.7	27.7

5	25	20	Reserve	29.102	28.30	-2.81	1423.0	1.5
1	24	21	Reserve	30.948	30.44	-1.66	1340.1	13.2
2	24	22	Reserve	30.38	30.32	-0.21	1124.6	80.5
3	24	23	Reserve	26.927	27.07	0.53	1327.4	95.1
4	24	24	Reserve	31.72	31.30	-1.34	534.2	35.3
5	24	25	Reserve	29.982	29.98	0.00	1248.8	17.4
1	23	26	Reserve	30.611	30.47	-0.46	1118.6	54.4
2	23	27	Reserve	29.776	29.22	-1.88	1422.4	31.4
3	23	28	Reserve	30.627	30.69	0.22	1068.7	30.8
4	23	29	Reserve	29.764	30.11	1.16	896.8	78.0
5	23	30	Reserve	27.643	26.80	-3.10	1046.1	43.7
1	22	31	Reserve	27.314	27.20	-0.42	762.6	36.4
2	22	32	Reserve	31.256	30.23	-3.34	1258.9	82.5
3	22	33	Reserve	26.918	26.69	-0.86	865.1	32.3
4	22	34	Reserve	28.333	27.74	-2.10	1173.9	21.4
1	21	36	Reserve	28.611	28.79	0.63	1294.5	5.9
3	21	38	Reserve	33.258	33.71	1.34	1274.3	99.4
4	21	39	Reserve	31.896	31.46	-1.38	725.0	7.5
2	20	42	Reserve	27.447	27.62	0.62	1150.3	91.8
3	20	43	Reserve	32.577	32.18	-1.23	1443.4	50.3
1	19	46	Reserve	33.474	33.42	-0.17	1229.8	81.8
2	19	47	Reserve	26.411	25.86	-2.12	705.5	180.0
4	19	49	Reserve	24.564	24.06	-2.08	994.5	28.9
5	19	50	Reserve	27.802	26.93	-3.18	1338.4	50.7
3	18	53	Reserve	27.489	26.73	-2.80	802.5	93.8
4	18	54	Reserve	25.274	25.38	0.43	1231.8	41.8