EFFECTS OF FATIGUE ON THE LOWER LIMB BIOMECHANICS DURING SINGLE LEG LANDING AMONG MALE RECREATIONAL ATHLETES

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By

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LIST OF ABBREVIATIONS

vGRF = Vertical Ground Reaction Force

SLL = Single Leg Landing

HR = Heart Rate

GRF = Ground Reaction Force

IC = Initial Contact

DKF = Dynamic Knee Flexion

ACL = Anterior Cruciate Ligament

EMG = Electromyography

CMJ = Counter Movement Jump

DLL = Double Leg Landing

ROM = Range of Motion

DKV = Dynamic Knee Valgus

FPPA = Frontal Plane Projection Angle

ASIS = Anterior Superior Iliac Spine

3D = Three Dimensional

RPM = Revolution per minute

RPE = Rate of Perceived Exertion

BMI = Body Mass Index

WHO = World Health Organization

SPSS = Statistical Package for Social Sciences

CPR = Cardiopulmonary Resuscitation

ABSTRACT

Most landing studies focused on several common biomechanical variables to characterize the role of different factors in injury. These variables include the joint kinematics and peak vertical Ground Reaction Force (vGRF). Peak vGRF may elaborate internal loads that may cause injury if not sufficiently distributed or attenuated by the musculoskeletal system. Furthermore, many studies have been conducted on the biomechanics of landing to determine the biomechanical factors that can minimize the impact forces and knee loading during landing. However, studies about the effects of fatigue on lower limb biomechanics during single leg landing (SLL) are scarce. Therefore, this study has been conducted to know the effects of fatigue on the lower limb biomechanics during SLL among male recreational athletes (i.e., volleyball, basketball, handball, and badminton). Fifteen participants joined the study voluntarily. Thirteen of them were recruited after anthropometrical screening. The participants performed Single Leg Landing (SLL) test (i.e., maximal effort countermovement jump from the ground) with three-dimensional (3D) motion capture before and after performing the fatigue protocol. During the fatigue protocol, participants were considered to achieve fatigue when their heart rate (HR) reached 90% of their age-calculated maximum heart rate, or when they cannot continue to perform rope skipping anymore. The sagittal plane knee joint kinematics and GRF was evaluated using the Qualisys Motion Capture Systems. The kinematics and GRF were compared at three landing phases (i.e., Maximum vGRF, 1st peak, and 2nd peak of vGRF). Paired T-test and Wilcoxon-Signed Rank test were used in this study to know if there were any significant differences in knee kinematics and GRF between pre- and post-fatigue. Based on the tests, there were no significant effects of fatigue on sagittal plane knee kinematics at all landing phases. For GRF, there were no significant effects of fatigue on the vGRF at landing phases 1st peak and 2nd peak of

vGRF, however, there was significant effect of fatigue on the vGRF at landing phase maximum vGRF (MvGRF). Therefore, coaches and athletes are suggested to include more training that focuses on the correction of landing technique. For kinematics, coaches should focus on the improvement of knee flexion angle during landing with single leg, while for GRF, coaches should focus on the dissipation of forces at the knee.

ABSTRAK

Kebanyakan kajian tentang pendaratan menumpukan pada pembolehubah biomekanik yang biasa untuk mencirikan peranan faktor-faktor berbeza dalam aspek kecederaan. Pembolehubah ini termasuklah kinematik dan “vertical ground reaction force” maksimum (MvGRF). Faktor MvGRF ini mungkin menjelaskan beban dalaman yang boleh menyebabkan kecederaan jika tidak diamalkan dengan betul. Tambahan pula, banyak kajian telah dijalankan terhadap biomekanik pendaratan untuk menentukan faktor biomekanik yang dapat mengurangkan daya impak dan lutut semasa pendaratan. Namun, kajian tentang kesan kelesuan terhadap biomekanik bahagian bawah badan semasa pendaratan kaki tunggal (SLL) adalah sukar didapati. Kajian ini telah dijalankan untuk mengetahui kesan kelesuan terhadap biomekanik bahagian bawah badan semasa pendaratan kaki tunggal dalam atlet rekreasi lelaki (i.e., bola tampar, bola keranjang, bola baling, dan badminton). Lima belas orang peserta menyertai kajian ini secara sukarela. Tiga belas daripadanya telah dipilih selepas saringan antropometri. Peserta melakukan ujian pendaratan kaki tunggal (SLL) sebelum dan selepas melakukan protokol kelesuan. Semasa protokol kelesuan, peserta dianggap telah mencapai tahap kelesuan apabila kadar denyutan jantung (HR) mereka mencapai 90% daripada kadar denyutan jantung dikira-umur maksimum, atau apabila mereka tidak mampu meneruskan lompat tali lagi. Kinematik sendi lutut pada satah sagittal dan GRF telah dinilai menggunakan Qualisys Motion Capture Systems. Kinematik dan GRF tersebut telah dibandingkan di antara tiga fasa pendaratan (i.e., “vertical ground reaction force” maksimum, puncak pertama, dan puncak kedua “vertical ground reaction force”). Ujian “paired-T” dan “Wilcoxon-Signed Rank” telah digunakan dalam kajian ini untuk mengetahui jika terdapat sebarang perbezaan penting dalam kinematik lutut dan GRF di antara pra dan pasca kelesuan. Berdasarkan ujian-ujian tersebut, tidak ada kesan kelesuan penting terhadap kinematik

lutut pada satah sagittal di semua fasa pendaratan. Bagi GRF pula, tidak ada kesan kelesuan penting terhadap GRF pada fasa pendaratan puncak pertama dan kedua vGRF, namun, terdapat kesan kelesuan penting terhadap GRF pada fasa pendaratan MvGRF. Oleh itu, jurulatih dan atlet disarankan untuk melibatkan lebih banyak latihan yang menumpukan pada pembetulan teknik pendaratan. Dalam kinematik, jurulatih perlu menumpukan pada sudut kelenturan lutut, manakala dalam GRF, jurulatih perlu menumpukan pada peleraian daya pada lutut.

CHAPTER 1

INTRODUCTION

1.1 Background of Study

In sports such as basketball, netball, frisbee and volleyball, jumping and landing are very common. The landing stage, which is a moment of contact between the feet and the ground, is a significant skill in these sports. Improper or awkward landing steps can lead to injury. For example, a lot of repetitive jump-land movements are involved in running. These jump-land movements are carried out at a success rate of 1500 times per mile (930 times per km) (Dufek and Bates, 1991). On the other hand, volleyball is a sport with a combination of aerobic and anaerobic energy systems and involves a lot of jumping and landing motion throughout the whole match. This jump-land locomotion is applied during spiking, blocking, and setting the ball. A study also showed that subsequent movement after landing was executed lead to increased risk of injuries (Zahradnik et al., 2018).

Biomechanically, landing from a jump consists of a few stages, such as initial contact (IC), maximum vertical ground reaction force (vGRF) and dynamic knee flexion (DKF) angle (Sahabuddin et al., 2021a). Initial contact (IC) is the phase when the feet completely hit the ground either to absorb the impacts from jumping or to load up the force to the ground for the next jumps. For maximum vGRF, increment of knee flexion angle during landing will lead to reduced GRF which is essential for reducing risks of injuries (De Vita and Skelly, 1992; Myers et al., 2015).

The lower extremity, particularly at the ankle and knee joints, is vulnerable to injuries during movements involving repetitive landings. One major reason is that during those landing activities, for instance landings after a basketball layup, a volleyball block jump or a gymnastics somersault, the lower extremity is exposed to vGRF amounting to 3.5–11 times body weight (Puddle and Maulder, 2013). When landing after fatigue, the knee flexion angle is greater at IC, peak GRF is greater, and required longer time to stabilise the body after landing (Brazen et al., 2010). Fatigue also poses greater risks of injuries such as anterior cruciate ligament (ACL) injury, due to it changing the landing mechanics, where the fatigued person lands with the worse alignment compared to when not fatigue (Liederbach, 2014). Moreover, Cortes et al. (2007) reported a more erect landing posture after fatigue, which is considered as a risk factor for ACL injury.

According to Ford et al., (2003), female athletes landed with greater total valgus knee motion and a greater maximum valgus knee angle than male athletes. GRF data showed greater power in males, while EMG data portrayed that both male and female applied different strategies of muscle activity during speed approach and planting angle on dominant leg prior to a jump (Fuchs et al., 2019). It has been shown that there are more males than females who are involved in sports, so the male athletes are more prone to injuries (Fuchs et al., 2019). Freshwater (2019) reported that athletes can suffer both physically and emotionally with a decrease in their quality of life when they sustain injuries associated with time loss from their sport. 5.2 million Australians have been reported to be financially burdened by sports injuries and had cost AU$2 billion to the Australian healthcare system (Medibank, as cited in Joseph et al., 2017).

Although several studies about single leg landing (SLL) have been published, data on the influence of fatigue on lower limb biomechanics during SLL are still lacking. Comparison between pre- and post-fatigue protocol is also still uncommon, despite that this landing type is typically used across multiple sports. The aim of this study is to provide data on the effects of fatigue on the biomechanics of lower limb during SLL. This study will also provide the comparison of onset of fatigue between athletes and how it increases the risks of injuries. Furthermore, this study will also evaluate the physical fitness of the participating athletes. This information may assist the athletes and coach to develop suitable training programmes to prepare the athletes.

1.2 Research Objective

1.2.1 General Objective

To compare the effects of fatigue on the lower limb biomechanics during single leg landing among male recreational athletes.

1.2.2 Specific Objectives

1) To compare the knee kinematics at sagittal plane during single leg landing before and after fatigue among male recreational athletes.
2) To compare the ground reaction force (GRF) during single leg landing before and after fatigue among male recreational athletes**.**

1.3 Research Hypotheses

Specific Objective 1: To compare the knee kinematics at sagittal plane during single leg landing before and after fatigue among male recreational athletes.

Null Hypothesis (H_o): There are no differences in the knee kinematics at sagittal plane during single leg landing between before and after fatigue.

Alternative Hypothesis (H_A): There are differences in the knee kinematics at sagittal plane during single leg landing between before and after fatigue.

Specific Objective 2: To compare the ground reaction force (GRF) during single leg landing before and after fatigue among male recreational athletes.

Null Hypothesis (H_o): There are no differences in the ground reaction force (GRF) during single leg landing between before and after fatigue.

Alternative Hypothesis (H_A): There are differences in the ground reaction force (GRF) during single leg landing between before and after fatigue.

1.4 Problem Statement

During the action of landing, it was recorded that there is an increment of GRF of about three to five times of the body weight. This elevation of impact force may cause strain to the surrounding muscle tissue on the lower extremities and causes the leg to push into valgus position (Seymore et al., 2019). Liederbach et al., (2014) observed that the peak knee valgus moment in Irish dancers increased after fatigue, which may increase the risks of ACL injury. Furthermore, greater knee flexion at initial contact, higher peak vGRF, and longer time to stabilise the body after 0.36 m single-leg drop landings are noticed during after fatigue (Brazen et al., 2010), which may be the cause of injuries among athletes. Despite these findings, studies that investigate the effects of fatigue on lower limb biomechanics in single leg landing following an explosive jump from the ground – a common type of landing in many competitive sports – particularly among male athletes are scarce. This study aims to investigate the technique utilised by recreational male athletes during landing when fatigued that may expose them to the risks of injuries.

1.5 Significance of Study

In many sports such as basketball and volleyball, jump-land motion is observed and considered to be a significant skill due to repeated movements or the nature of the sport. Single leg landing has shown to be causing higher number of lower limb injuries compared to double leg landing (Wang, 2011). By investigating the effects of fatigue on biomechanics of single leg landing, a better understanding on technique and landing strategy can be achieved. The study protocols which use natural jump height, commonly known as maximal counter movement jump (CMJ) can provide a more realistic movements that is similar to the real game situation. The execution of single leg landing after fatigue is achieved often represents more of the natural movements of the athletes during play, which lead to many injuries. Through this study, athletes can gain benefits from the data obtained. They can identify which biomechanical factor of their landing movement that is inefficient when fatigue that may be harmful to them. Coaches can also benefit from this study, where they can plan a suitable injury prevention programme which can contribute not only to the athletes, but the whole community as well.

1.6 Operational Definition

Table 1.1: Operational definitions

Abbreviations	Operational definition
Dynamic Knee Valgus	The combination of hip adduction, hip internal rotation, knee flexion, knee external rotation, knee abduction, ankle inversion and ankle dorsiflexion during dynamic motions.
Recreational Athletes	University students that participate in specific sports (volleyball, frisbee, netball, basketball) and plays for health-related purposes.
Maximal Effort Counter Movement Jump (CMJ)	Jumpers making an upright standing position first and then makes a preliminary downward movement by flexing at the knees and hips, then immediately extends the knees and hips again to jump vertically up off the ground by executing thehighest height that individual able to.
Fatigue	A point where 1) The participants' HR had reached 90% of their age-calculated maximum HR (maximum HR estimated as 220 – age) or 2) The participants cannot continue to perform rope skipping (Ramos-Campo et al., 2017). Rate of perceived exertion (RPE) is also taken before and after fatigue.

CHAPTER 2

LITERATURE REVIEW

2.1 Single Leg Landing

In sports like volleyball, basketball, and gymnastics, landing-related injuries are common (Harringe et al., 2007). Landing maneuvers such as single-leg (SLL) and double-leg (DLL) are performed to attenuate the large landing impact in the lower extremity joints (Coventry et al., 2006). Single-leg landing has been a more common technique in sports (Wang, 2011). Both landing techniques adopt different energy dissipation strategies in the sagittal and frontal planes (Sahabuddin et al., 2021b). However, considering the prominent frontal plane biomechanics exhibited by the knee during SLL, may have more likelihood of leading to traumatic knee injuries, particularly non-contact ACL injuries, compared to DLL (Yeow et al., 2011). Yeow et al. (2011) also stated that in the sagittal plane, the hip and knee were the main energy dissipators during DLL, while the hip and ankle were dominant energy dissipators during SLL. In the frontal plane, the hip acted as the key energy dissipator during DLL, while the knee contributed the most to the energy dissipation during SLL (Yeow et al., 2011). The knee also exhibited greater frontal plane joint ROM, moment, and energy dissipation during SLL than DLL (Yeow et al., 2011).

Studies by Decker et al., (2003) and Zhang et al., (2000) showed that the energy dissipation on the lower extremities during landing can be influenced by various factors, such as gender, landing height, and also landing stiffness. De Vita et al (1992) demonstrated that the hip and knee muscles were major contributors to energy dissipation during soft-style landing from a 0.59-m height. Soft-style landing is characterised by the greater knee flexion angle (>90°) and smaller vGRF. For stiff-style landing, defined by the smaller knee flexion angle (<90°) and greater vGRF, the ankle muscles absorbed more energy than the hip and knee muscles. Zhang et al (2000) further illustrated that the hip and knee extensors served as major shock absorbers during DLL from heights of 0.32–1.03 m. For gender influence, Decker et al (2003) found that the knee was the primary shock absorber for both genders during DLL from a 0.6-m height, while the ankle plantarflexors and the hip extensors were the second largest contributors to energy absorption for the females and males, respectively.

2.2 Effects of Fatigue on Lower Limb Biomechanics

Fatigue clearly affects lower body biomechanics during SLL. When landing after fatigue, participants had greater knee and ankle flexion angles at initial contact, greater peak ground reaction forces, and required longer time to stabilise the body after landing, regardless of sex (Brazen et al., 2010). Zhang et al (2018) also stated that the range of motion (ROM) of the hip was significantly greater when the athletes were fatigued.

Fatigue also affects lower body biomechanics during DLL. A study by Jayalath et al (2018) showed that when comparing ankle biomechanics between a fatigued and non-fatigued condition, findings suggested that at initial contact of landing, the ankle plantarflexion increased in double legged jump. At maximum knee flexion after landing, dorsiflexion decreased in double legged jumps (Jayalath et al., 2018). Also, ankle power and ground reaction force are reduced at initial contact to maximum knee flexion at landing after fatigue. The study by Jayalath et al (2018) aimed to investigate the effects of fatigue on the ankle biomechanics, while this study aims to investigate the effects of fatigue on the knee kinematics.

Lower body biomechanics during landing tasks are also affected by factors such as gender and type of sports played by athletes. For type of sports played, Liederbach et al (2014) stated that dancers are more resistant towards lower extremity fatigue compared to team sport athletes, so this may partially explain the lower incidences of ACL injuries among male and female dancers as compared to team athletes. However, fatigue does change the landing mechanics of both dancers and team athletes, such that both groups landed with worse alignment after being fatigued (Liederbach et al., 2014).

Gender also plays a role in the lower body biomechanics during landing tasks. In a study by Gehring et al (2009), it is shown that during DLL, females landed with an increased knee flexion velocities and knee joint abduction angles. They observed that compared to males, females showed different muscle activation patterns such as a delayed activation of the lateral hamstring and the vastus lateralis muscle during the preparatory phase of the landing. The authors also noted that fatigue also led to a reduced pre-activation of the medial and lateral hamstrings and the gastrocnemius muscle both in males and females. On the contrary, Sahabuddin et al., (2021a) observed no significant kinematical differences across gender and landing heights during fixed height drop vertical jump among those with normal range of dynamic knee valgus (DKV).

2.3 Common Injuries Related to Landing

Biomechanical factors observed from a poor technique of landing such as high impact loading, sudden decelerations, and high vertical ground reaction forces (GRFs) predispose athletes to lower limb injuries and pain such as ACL injury (Myers et al., 2015). ACL injuries have a reported prevalence rate of 85 over 100,000 people per year which contributed as one of the most common injuries in sports (Ardern et al., 2016). A study from Wesley et al., (2015) also suggested that females have higher risk of suffering from ACL injury compared to men, due to more errors in landing technique compared to men.

Dynamic knee valgus (DKV) is a mechanism of medial knee collapse due to a combination of hip internal rotation, hip adduction, knee valgus, and external rotation of the tibia during dynamic motions such as jump-landing (Wilson and Davis, 2008). The normal range of DKV is 7-13° for females and 3-8° for males (Munro et al., 2012). One is said to have excessive DKV if it exceeds the range. DKV is measured by observing the 2-Dimensional knee Frontal Plane Projection Angle (FPPA), which is the intersection of the line created between ASIS and centre of knee joint and the line between the centre of knee joint and the centre of ankle joint (Jamaludin et al., 2020).

Kinetic chain theory states that abnormalities of a joint may influence risks of injuries in other joints as observed in excessive DKV (Pattyn et al., 2011). Dynamic knee valgus (DKV) is related to kinetic chain motion, where the medial motion of the knee joint, tibia abduction, and foot pronation can occur due to excessive frontal and transverse motion of the hip (Jamaludin et al., 2020). The influence of proximal joint such as hip and trunk on knee motions is called top-down causes of excessive DKV (Sharma et al., 2010). Tibiofemoral alignment can be assessed for DKV during static and dynamic position by using 3D motion capture system and force platform. Tibiofemoral alignment may reflect varus or valgus static alignment (Sharma et al., 2010). It was shown that weakness of hip musculature was associated with greater knee valgus during single leg ballistic and single leg squat tasks (Dix et al., 2019). Khamis et al (2007) also stated that DKV is often associated with the top-down kinetic chain of lower limbs. For instance, decreased isometric strength of hip abductors, adductors, and extensors was closely correlated with increased peak valgus angle at the knee (Abdullah, 2016).

Other than top-down, there is another type of kinetic chain related to DKV, which is bottom-up kinetic chain. Regarding this kinetic chain, weakness of ankle musculature and foot structure may cause a lack of control at the knee joint and thus increase risks of knee injuries (Jamaludin et al., 2020; Khamis et al., 2007). Reduced dorsiflexion ROM is linked to increased knee valgus excursion during landing (Nigg et al., 2017) and altered landing mechanics that predisposed athletes to injury (Mason-Mackay et al., 2017). Deficits in ankle dorsiflexion ROM may occur due to the decreased extensibility of the gastrocnemius/soleus complex and restricted posterior talar glide on the tibia, thus creating DKV (Fong et al., 2011). A significant correlation was found between ankle dorsiflexion flexibility and the peak knee abduction angle ($r = 0.355$, $p = 0.048$) during landing (Lopes et al., 2017). Moreover, individuals with greater ankle dorsiflexion ROM demonstrated smaller GRFs and greater knee-flexion displacement during landing, which may be associated with a reduced risk of anterior cruciate ligament (ACL) injury (Malloy et al., 2014).

Although there are several studies on lower limb biomechanics, information on how fatigue affects the lower limb biomechanics is still lacking, particularly during SLL maneuver. This study needs to be done so that further understanding will be gained. Athletes will also gain benefit from this study, as they can figure out a better landing movement when fatigued that can reduce the risks of lower extremity injuries, especially

ACL injury.

CHAPTER 3

METHODOLOGY

3.1 Study Design

This was a cross sectional study. The purpose of this research is to compare the effects of fatigue on the biomechanics of single leg landing (SLL) among male recreational athletes. 15 male recreational athletes in USM Health Campus (PPSP; PPSG; PPSK) were involved in the study. The study protocol was approved by USM/JEPeM/21010028. The data collection procedure was conducted at Exercise and Sports Science Lab PPSK, USM Health Campus, Kubang Kerian with the time allocation of one hour for each participant.

3.2 Sample Size Calculation

Sample size calculation was done using G*Power Software (v.3.1.9.2, Universität Düsseldorf, Dusseldorf, Germany), a software that is free to use, to calculate statistical power. The margin α-error was fixed at 5% with confidence interval of 95%. After using G*Power Application and referring to study by Bhalerao & Kadam (2010) to calculate the sample size, it was known that the sample size needed for this study is 10, with an additional 5 participants. The variable used as reference is the knee flexion angle during peak posterior GRF moment (p=0.001). The statistical analysis that used was paired T-test. 15 participants were recruited by inclusion of estimated 50% drop out.

3.3 Study Participants

3.3.1 Inclusion Criteria

This study involved 15 male athletes who play volleyball, frisbee, netball or basketball at recreational level. The participants were briefed beforehand regarding the study procedure. Participants also signed the consent form on medical treatment section truthfully and informed the researcher immediately if there was any occurrence of health-related problem during the study period.

Inclusion Criteria

- Aged 18 to 25 years old.
- Plays volleyball, basketball, netball or frisbee at recreational level.
- Regularly train for at least three times per week in related sports.

3.3.2 Exclusion Criteria

Exclusion Criteria

- Have any severe lower limb and/or back injuries for the past six months that require surgery.
- Not recommended by physician to participate in any physical activity.

3.3.3 Recruitment of Participants

Volleyball, basketball, handball, and badminton athletes were chosen for this study because these sports require a lot of repetitive jump-land movements. Recreational athletes were chosen to ease the recruitment phase. This is because most of the university athletes cannot be recruited due to the following reasons: i) they have graduated, ii) have other commitments such as academics, or iii) are recovering from injuries. Also, due to the current global pandemic situation, not all of the athletes were present at the university.

Purposive sampling method was applied. Recruitment was conducted by advertising the research project through poster and word of mouth. Detailed explanation was given prior to the participation. Only volunteers were recruited.

3.4 Study Protocol

The aim of the study was to compare the effects of fatigue on the lower limb biomechanics during single-leg landing test among male recreational athletes. The volunteers that fulfilled the required criteria were recruited for the study. The flowchart of the study was shown in the figure 3.1.

Recruitment of participants (N = 15)

Population with the inclusion criteria will be included as participants

Warming Up

- Participants will undergo warming up session for about 5 minutes.
- Participants will be asked to cycle at 60 RPM with work rate of 50 Watts, followed by stretching and 5 times squat jumps.

Test Protocols

- Participants will perform 3 times maximal double leg jumping without heights and then execute single-leg landing of the dominant leg on the force platform.
- For fatigue protocol, participants will be asked to do rope skipping.
- Their heart rate will be monitored by wearing HR belt monitor on their chest.
- Participants will be considered to have achieved fatigue when their HR reached 90% of their age-calculated maximum HR, or when participants cannot continue rope skipping.
- The highest HR or fatigue protocol time will be recorded. The HR and rate of perceived exertion (RPE) will be taken immediately before and after the fatigue protocol.
- A rest period of 15 minutes will be given after the fatigue protocol.
- After fatigue protocol, participants will be asked to do 3 trials of countermovement jumping (CMJ) again.

Cooling Down

- Participants will perform cool down for 5 minutes by cycling on an unloaded cycle ergometer at 60 RPM.

Based on data collected, data analysis and statistical analysis will be done.

Figure 3.1: Flowchart

3.4.1 Physical characteristics of participants

Participants were advised to have enough sleep of at least 6 hours the night before the testing. Participants were also reminded to have their meals at least 2 hours prior to the session, and intake of caffeine was prohibited. Participants were also reminded to wear tight fitting clothes, so that the retroreflective markers stay in place and more accurate measurements will be obtained.

Prior to entering the laboratory, participants were required to fill the COVID-19 Risk Declaration Form, as to comply to the standard operating procedure for COVID-19 screening set by Health Campus. Participants underwent temperature check. If their body temperature is 37.5°C and higher, they were not allowed to enter the laboratory for data collection session. For each session, only one participant was present.

Physical check-up was done to the participants such as body height, weight, body fat percentage and leg length. The dominant leg of participants was recorded. To determine the participant's dominant leg, they were asked on which leg they would use to kick a ball (Graci et al., 2012). Body weight (kg) and height (m) were measured by using digital medical scale (Seca 769, Hamburg, Germany). Body fat percentage was calculated using Electronic Body Fat Percentage Analyzer (Omron HBF-375, Kyoto, Japan), and length of leg segments was measured using measuring tape. The distance (cm) between anterior superior iliac spine (ASIS) and ipsilateral medial malleolus were quantified as the length of leg segments. The length of leg segments was also measured in both standing and supine positions. At the end of the study protocol, participants were given honorarium as a token of appreciation for their participation in the study.

3.4.2 Single Leg Landing Test

Before starting the test, participants were asked to do warming up for 5 minutes on the cycle ergometer (Cybex Inc., Ronkonkoma, NY, USA). The cycle ergometer was set at 50 Watts resistance and participants were required to cycle at velocity of 60 RPM constantly throughout the warming up session. Then the participants were asked to do 5 times ballistic jumps. Warming up session was essential to reduce risks of injuries, by preparing the muscles, tendons, joints, and bones for the activity and will likely improve performance compared to no warming up.

Researcher had placed 35 retroreflective markers (25-mm diameter) on the participants' lower leg, as instructed by the Plug-in-Gait Marker Set, specifically on the sacrum, bilaterally on ASIS, medial and lateral thigh, medial and lateral femoral epicondyle, lateral shin, calcaneus, medial and lateral malleolus and second metatarsal for static measurements (Figure 3.4.2.2). Six markers were then removed for dynamic measurement or actual testing. Researcher had demonstrated the testing exercises first so that the participants will have better understanding on what they need to do. Then the participants were allowed to have a practice session. When participants felt there are no difficulties in executing the SLL, the researcher proceeded with the actual testing of the 3D test.

Participants were asked to perform Counter Movement Jump (CMJ) of both legs as high as they can during the actual testing (Figure 3.4.2.1). Any external aid for alleviation such as drop jump box was not used. In executing the maximal effort CMJ, participants stood on the force platform with both feet slightly apart, depending on their comfortability. Then they slightly bent down and jumped as high as they can. Participants were required to land with their dominant leg on the force plate (Kistler, Winterthur, Switzerland). Participants were recommended to apply natural landing style, where the forefoot touches the ground first and bend the knees slightly to reduce risks of injuries. Participants performed the CMJ bare footed.

Participants began their jump based on the instruction given by the researcher and were given 5 minutes of rest between trials. Participants were required to complete 3 trials for the test. A trial was considered successful when the participants jumped without any external aid or supporting leg and landed with a stable landing posture. For any unsuccessful trials or any error occurred during the data collection after the testing session, the participants were asked to redo the trials or procedure. During the entire test, the researcher was present to help with the data measurements and helped to provide guidance, instruction and observed the participants' performance during the test procedure.

When the participants completed the trials, they were asked to do 5 minutes of cycling on the unloaded Cycle Ergometer at 60 RPM as a cooling down session. Participants were also required to do stretching on the leg muscles used during the test.

Figure 3.4.2.1: Single-leg landing maneuver.
Image from http://wise-coach.com/measurements/counter-movement-jump.html

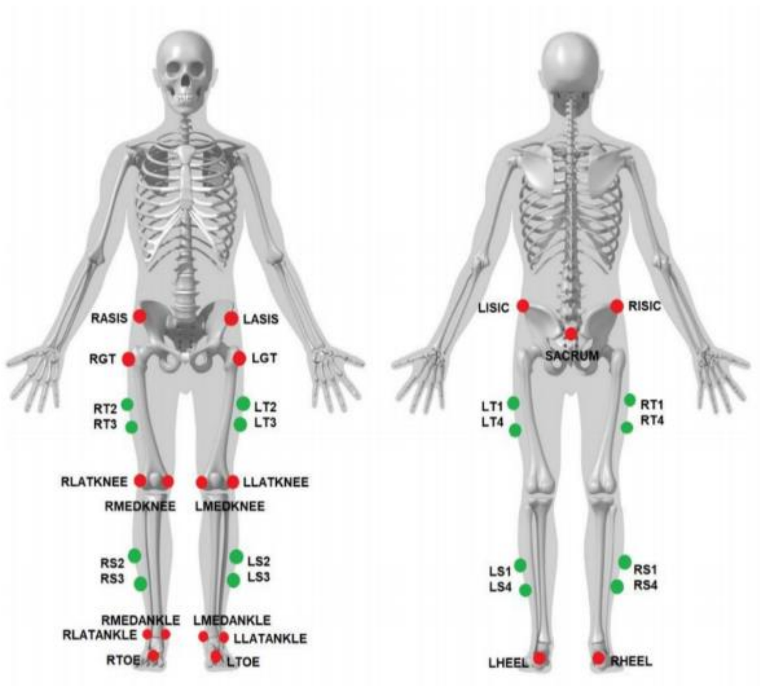

Figure 3.4.2.2: Gait module sample and marker's placement for lower limb.
Image from https://www.qualisys.com/software/analysis-modules/

3.4.3 Exercise-Induced Fatigue Protocol

Participants were asked to perform pre-fatigue SLL trials after they had done warming up. After pre-fatigue SLL trials, participants wore a heart rate (HR) monitor, and their pre-fatigue HR were recorded. Heart rate (HR) transmitter belt monitor was attached to the participants' chest to monitor their heart rate throughout the entire fatigue procedure. Then, they performed exercise-induced fatigue protocol involving rope skipping based on methods by Zhang et al., (2018). Participants were considered to have achieved fatigue, and the procedure was terminated when the following two criteria were met: 1) The participants' HR had reached 90% of their age-calculated maximum HR (maximum HR estimated as 220 – age) and 2) The participants cannot continue to perform rope skipping (Ramos-Campo et al., 2017). The rate of perceived exertion (RPE) was taken immediately before and after the fatigue protocol. These fatigue criteria were based on Zhang et al., (2018) who conducted similar study design to the current study.

3.5 Data analysis

The included data for anthropometry to be used were height, weight, body mass index (BMI), body fat percentage and length of dominant leg segment. These data were recorded and analysed. Medical scale (Seca 769, Hamburg, Germany) was used to record the body mass index (BMI) and classified the data based on the norms from International Classification (WHO, 2021). Qualisys Track Software (Qualisys, Exave AB version 2.6.673, Gothenburg, Sweden) was used to identify and record the trajectory of the retroreflective markers. Inverse dynamics calculation was used after all the data had been collected. Further analysis using the software enabled researcher to identify kinematics and kinetics of lower limb variables in sagittal plane.