THE BIOMECHANICAL DEMANDS OF SNOWBOARD LANDINGS IN TRAINING WITH ELITE FREESTYLE SNOWBOARD ATHLETES

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ABSTRACT

Freestyle snowsport has emerged as one of the fastest growing Winter Olympic sports in the past decade, despite this no countries/teams have published data explaining the sports biomechanical demands in training or competition. Information describing the kinetic, kinematic and muscular demands relative to jump landing actions has not been investigated with elite freestyle athletes.

Data were collected from athletes of the Great Britain Park and Pipe team during an official team training session, conducted on an artificial landing slope. Five athletes were assessed over multiple trials in three jump landings completed in regular, switch, 360 degree (deg) rotation jump landings. Measures including; landing acceleration (g), knee flexion angle (deg), knee angular velocity (d/sec) and integrated electromyography (iEMG) in muscles of the upper-thigh (bicep femoris, rectus femoris, semitendinosus, vastus lateralis, and vastus medialis), in pre and post-initial contact (IC) phases of jump landings were recorded.

Large peak board accelerations were found in the regular and 360 deg rotation jump landing conditions, which corresponded with increased knee flexion angle and knee angular velocity at the point of initial contact (landing) and post-IC phase. Group summed mean iEMG revealed higher overall muscle activation post-IC versus pre-IC, and higher mean iEMG and peak % MVC recorded in the BF, RF, VL and VM muscles post-IC in the 360 deg rotation condition. Highest mean iEMG in the ST muscle was found post-IC in the regular jump landing condition. Elevated pre-activation of hamstring (BF, ST) muscles was found in switch and 360 deg rotation conditions. And, higher mean and peak iEMG values were also observed post-IC in the quadricep (RF, VL and VM) muscles.

This research can be used to inform practitioners of the biomechanical demands of snowboard jump landings, which is currently absent from the scientific literature. More specifically, the findings reveal the importance high muscular strength and rate of force development capabilities of hamstring and quadricep muscles, which should be targeted in athletic development programmes to assist lower-limb performance during snowboard landings.

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“Alone we can do so little, together we can do so much”.

(Helen Keller)

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GLOSSARY OF TERMS

Rider – Abbreviated term for a snowboarder.

Kicker – Name given to a large man-made slope used by snowboarders to perform aerial jumps.

Regular – Refers to landing in a regular stance, e.g. same leading leg at the nose of the snowboard at take-off and landing.

Switch – Refers to landing in a switch stance following a 180 degree spin. E.g. the rider jumps with their left leg leading, spins 180-degrees and lands with the right leg leading in a switch stance.

360 degree (deg) rotation – An action requiring a rider to perform a flat spin through 360 degrees landing in his/her regular stance, e.g. same leading leg at the nose of the snowboard at take-off and landing.

CHAPTER 1. INTRODUCTION

Freestyle snowsport has emerged as one of the fastest growing Winter Olympic sports in the past decade, with a record number of 5 freestyle events featuring at the 2014 Winter Olympic Games in Sochi, Russia: Slopestyle (SS) and Halfpipe (HP) ski and snowboard, Mogul Skiing, Aerial Skiing and Ski and Snowboard Cross (SBX). Progressive aerial events, like SS and Big Air, have encountered the largest growth in professional sport participation and an increased total number of professional competitions and media attention in the past few years. More countries have produced athletes capable of competing on the international scene than ever before. As such, national performance programmes have rapidly expanded in size and resource, with more teams working to create freestyle-specific training facilities and performance services to produce more talent capable of performing on the world stage. Several national teams have already begun to invest in more conventional high-performance support services, including sport science and strength and conditioning to investigate were applied science can support and impact upon freestyle performance. Although to date, no countries/teams have published data from freestyle athletes in training or competition, leaving a void in empirical evidence of the sports key physical demands. Of concern currently, is the high prevalence of sports injuries impacting elite male and female freestyle athletes sustained during falls and crashes. Presently, information describing the biomechanical (kinetic and kinematic) demands relative to a large jump-landing has not been investigated with elite freestyle athletes, leaving a gap in the knowledge. Greater awareness of the training and competition activity facing these athletes would greatly increase understanding and ability to offer evidence-based injury prevention/ performance solutions. This chapter will discuss the current literature linked with freestyle snowsport and present rationale for the investigation of biomechanical assessment of elite freestyle snowboard athletes in training.

2.1 Background of freestyle snowsport

Snowboarding originated in France as a recreational sport during the 1920's (Tiburg and Surfing, 1996) and became more popular in the mid 1960's with half of the world's eight million snowboard riders alone reported in the US, competing in regional competitions (Kipp, 1998). At this time, European competitions ran parallel to the programs of alpine skiing under the governance of the International Ski Federation (FIS) with the first world cup season launched in 1994. Later, the International Olympic Committee (IOC) claimed their interest to competitive snowboarding and introduced two events, namely, parallel giant slalom (PGS) and half pipe (HP) to the Nagano, Japan Winter Olympic Games 1998 (FIS, 2013a.). Today the competition scene of elite snowboarding has grown substantially with a vast stream of European, World Cup, Winter X Games and Olympic competitions completing an 8-month competition season from September through to April each year.

Snowboard events are categorized into two main disciplines, alpine (parallel slalom (PSL), parallel giant slalom) and freestyle (HP, slopestyle (SS) and big air (BA). Over time, the International Olympic Committee (IOC) has increased the number of events at Winter Olympic competition and a record high of five events took place at the 2014 Winter Olympic Games, Sochi, Russia. Whilst the profile for competition, sport participation and media attention has grown considerably in the past century, scientific literature investigating the sport has been slow to evolve by comparison. Because of this, a true understanding of the sports physical demands is still absent from the literature and therefore knowledge of best methods to physically prepare athletes for international competition remains unavailable.

2.2 Slopestyle event characteristics

Slopestyle snowboard competitions are characterised by explosive, ground and aerial free-flowing, acrobatic manoeuvres, including terrain features, rail slides and aerial boosting ‘kickers’ (Jumps) differing in shape and size *(see Figure 1)*. A World Cup and Olympic course comprise of 6-8 features over 3 sections, interspersed with short, flat transitions allowing set-up time between tricks *(see Figure 2)*. The layout of a SS course is designed to accommodate athletes increasing linear momentum, and so the features tend to increase in size as the course progresses, therefore increasing athlete flight time and velocity through latter parts of the course. Athletes compete individually in qualifying rounds through to finals comprising of 2-3 separate runs. The time between jumps in a single SS or HP run are brief, with 6-8 total features/jumps performed with full recovery (<15 minutes) between runs lasting 30 seconds on average. Athletes may be expected to repeat this activity across a 2-3 hour competition window depending on progress in each contest. Each contest includes 1-2 practice days, 1 qualification day, and a finals day. With travel to each competition event bookending practice and competition, fatigue is likely to impair athlete recovery and performance (Turnbull, 2013). Whilst there is some literature describing athlete demands during HP training and competition, there is no research available explaining time-motion or physical demands of athletes in SS training and/ or competition. Major differences exist between a HP and SS competition, such as course design, range of tricks and run duration performed by athletes. Given the differences listed, it is crucial that research is performed on SS athletes to add knowledge of demands currently absent from the literature.

Like gymnastics, freestyle athletes compete to gain points awarded to riders that utilise challenging features in a sequential and creative manner. Athletes endeavour to produce a well-balanced run, incorporating qualities established by the International Ski Federation, and include variety, combinations, execution, difficulty and amplitude, each contributing to overall impression. Deductions are made for missed features, mistakes, stops and falls/crashes. High scoring runs require athletes to ride the most technical course line, utilising a range of novel and progressive tricks including ‘board grabs’ through on/off axis rotations. Athletes capable of achieving podium spots at competitions like ‘Dew Tour’ at Breckenridge, Colorado, and ‘X-Games’ held in Aspen, need to produce the most advanced and progressive range of tricks within the field. For example, versions of the 'Triple Cork 1620', and the 'Backside 1080' *(see Figure 2)* (spinning backside 1080 degrees about their axis) has become increasingly common for athletes placed in the top 5 of competition within the last 3 years. Performing highly technical aerial manoeuvres is not without risk. Falls and crashes can often result in injury associated with extreme trauma to athletes, such as fractures and/or brain concussions. Based on the inherent injury risks associated with the sport, through a diversity of sport-specific skills training, athletes and coaches endeavour to reduce errors and risk of injury by developing sound jumping and landing skills concomitant with snow skills to reduce the prevalence of falls and crashes during training and competition.

The aim of this literature review is to discuss in the available literature describing the broad physical demands of SS athletes, more specifically, to critique information pertaining to the biomechanical demands linked to jumping and landing which underpin training and competition activity.

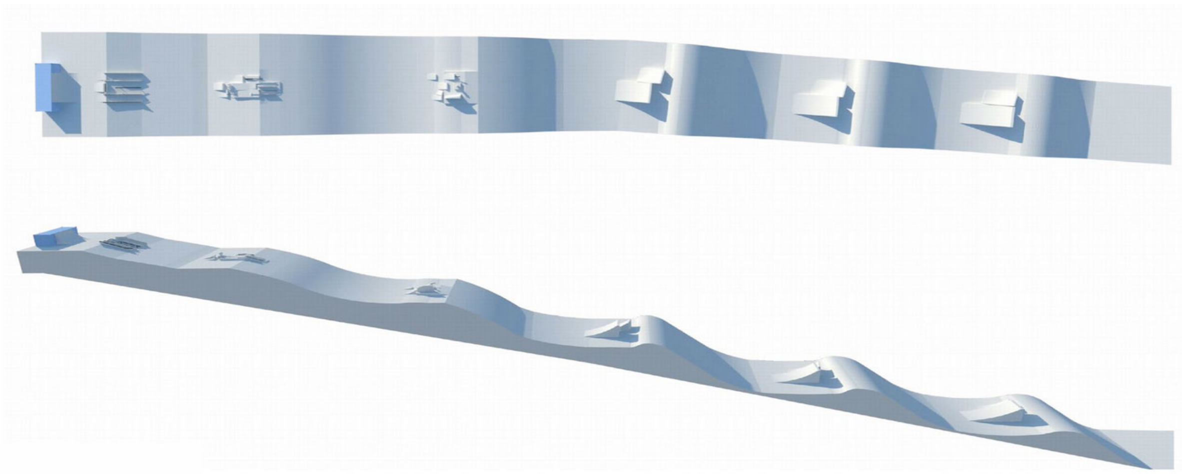

Figure 1. The Sochi Winter Olympics 2014 Slopestyle course, consisting of the rails section (three initial features), and the jumps section (three progressively larger kickers toward the bottom of the course). Photo: Jenny Bletcher.

Figure 2. Diagrammatic representation of the Sochi Winter Olympics 2014 Slopestyle course. The initial 3 features are rail sections followed by 3 "kickers" (jumps) increasing progressively in size.

Figure 3. "Backside 1080" trick; rotating backside 1080' on a large kicker, Stubai, Austria. Athlete: Jamie Nicholls, GB Park & Pipe Team. Photo: Jenny Bletcher.

2.3 Physiological demands

Literature investigating physiological demands of freestyle training and competition remains limited. Were information concerning SS demands is absent, sport science practitioners and coaches are forced refer to literature on snowboard SBX, HP and Alpine to gather missing information about the sport. To date, only two studies have examined the physiological activity of elite HP riders (athletes) in training (Kipp, 1998, Turnbull et al., 2011). Kipp (1998) measured physiological markers from elite snowboard athletes during a HP training session. Three male athletes from the U.S snowboard national team were assessed during a single 60-minute snow training session. Blood lactate values of 2.9 mmol L^{-1} were reported at the end of every third training run throughout the 60-minute session. Riders heart rate responses showed peak elevations of 92% of snowboarder’s age predicted maximum, indicating significant anaerobic contribution. Session average heart rate measured 140 beats per minute (bpm), suggesting this HP training session was predominantly aerobic in nature. Commonly, snow-based sessions last in the region of 3-5 hours, with 10-20 laps of the park completed. And also include extended periods of hiking between training runs, sometimes climbing steep alpine terrain, requiring significant aerobic fitness to sustain this activity for extended periods (Kipp, 1998, Żebrowska et al., 2012, Turnbull, 2013). While the data presented by Kipp (1998) limits our understanding of the cardiovascular demands, this study remains the only published work to show physiological markers obtained directly from elite snowboard athletes in the field. To date, there has been no reported data on heart rate (HR) responses on athletes in elite freestyle competition.

The first study to perform a physiological profiling assessment on professional snowboard athletes was conducted by Platzer et al. (2009). Using 37 athletes (21 men and 16 women) from the Austrian snowboard team competing in snowboard cross (SBX), parallel slalom (PSL), HP and BA the authors attempted to establish a relationship between performance in lab tests compared to results obtained in competition. The battery included tests measuring aerobic fitness, balance, jumping, core and leg power, upper-body strength and a snowboard start simulator. Overall, authors found the test battery to be a good predictor of SBX FIS points in female, but not male athletes. The strongest prognostic test was the maximum push-off speed, as measured by the snowboard start simulator, which is unsurprising given the importance of this maneuver during SBX race starts. In addition, aerobic fitness recorded by analysing relative power from the last stage of the incremental bicycle ergometer test (3.48 $W \cdot Kg^{-1}$ for women, and 3.8 $W \cdot Kg^{-1}$ for men) was the best predictor for overall WC points across all performance disciplines. Similar values have also been seen by elite Polish snowboarders in the bicycle ergometer maximal aerobic capacity test (VO_{2max}) for women (3.7 $W \cdot Kg^{-1}$) and men (4.4 $W \cdot Kg^{-1}$) (Żebrowska et al., 2012). This supports the consideration that snowsport athletes possess a well-developed aerobic system as proposed by Kipp (1998) probably acquired from long snow training sessions (<5 hours) incorporating brief periods of high-intensity. The bicycle ergometer test provides a good crossover to sport-related musculature and recruitment over treadmill running tests, further, the predominance of ankle and knee injuries in snow sport athletes make this a preferential test and training method over impact related methods, such as running (Turnbull et al., 2009). Unfortunately, the Platzer et al. (2009) investigation did not examine SS snowboard athletes and therefore does not offer consideration for differences between HP and SS snowboard athletes. Despite the lack of physiological studies to date, future investigations examining athletes in training are important to define SS snowboard demands. This information could be of great significance to sports coaches when designing physical training programs to prepare athletes for the demands of training and competition (Turnbull, 2013).

Snow training often takes place at high altitude environments (<3000m above sea level) at venues like Breckenridge, Colorado, USA, where the reduced oxygen availability up-regulates glycolytic rates. This in turn reduces glycogen stores and strains the anaerobic system from supplying energy for high force dependent activities, like jump landings (Turnbull et al., 2009, Seifert et al., 2009). With this in mind, it should be considered that enhanced anaerobic and aerobic capacities, supporting fast twitch type II fibres, may reduce peripheral limitations placed on the leg muscles to prevent a decrease in performance of repeated jump landing tasks. It is currently unknown if concentrated snow-based training cycles provide sufficient conditioning stimulus for elite athletes competing in World Cup competitions.

2.4 Injury prevalence

Despite a lack of knowledge around the physical demands of freestyle snowsport on male and female athletes, evidence reporting the type and frequency of sports injuries is readily available. Several epidemiological studies point out a greater number of injuries are sustained by riders than freeskiers (Torjussen, 2006, Flørenes et al., 2010, Flørenes et al., 2012). In addition, the evidence shows a consistently high prevalence of knee injuries above all other injured sites, across all freestyle disciplines. Knee and in particular ACL injuries account for 38% of all reported injuries in elite freestyle athletes (Flørenes et al., 2010). Injuries sustained to the head/face (concussion) injuries rank second highest, followed by chest/rib and shoulder injuries as the most frequently injured body parts amongst freestyle athletes (FIS, 2016). The frequency of total injuries sustained in training and competition are reportedly higher than alpine skiing (4.0 every 1000 days) with 4.1-6.3 injuries occurring every 1000 days on average (Flørenes et al., 2012). The frequency of head injuries from falls and crashes are reportedly similar across alpine skiing and freestyle disciplines, with findings ranging from 10-14% across groups (Steenstrup et al., 2014). With no information discussing injury related factors in freestyle athletes it is difficult to identify key threats facing this population. With a clearer understanding of the sports biomechanical demands, the role between athletic preparation in the prevention of injuries could be investigated.

Currently it is unknown if the aerial requirements of freestyle pose greater risk to these athletes over Alpine Skiers, although the higher volume of training conducted on aerial features in terrain parks is undoubtedly an important risk factor for consideration. Given the high load, high eccentric force demands linked with jump landings (Berg et al., 1995a) it should be noted athletes with greater eccentric leg strength and rapid force absorption capabilities may have a greater capacity to absorb landings and reduce crashes over weaker individuals. Because females have reportedly lower eccentric leg strength than males during landing tasks (Lephart et al., 2002) it is logical to consider that females are at greater risk of injury than males. Evidence describing peak landing impact and muscular load associated with snowboard jump landings is essential to bring greater understanding to this area.

The most common injury mechanism associated with head trauma results from an over/under-rotation in aerial jumping, causing the “backslap episode” were the upper back and head make direct contact with the ground. Direct and rotational acceleration impacts have been recorded during backslaps in aerial skiers ranging between 27 to 92g (Mecham et al., 1999). There have been 2 fatal head injuries in International Ski Federation World Cup competition in recent years and therefore traumatic head injuries are an ongoing concern for the freestyle community. Athletes reportedly miss around 4 weeks of total training time after sustaining a head injury, with female athletes reportedly at 1.5 times greater risk of sustaining head injuries than males (Steenstrup et al., 2014). Whilst there are inherent risks facing freestyle athletes research that describes the biomechanical demands occurring in snowboard jumping and landing is warranted. It is currently unknown if skill errors in take-off, during flight or landing moments increase the risk of crashing and the potential for impact related injuries. Armed with more qualitative knowledge, coaches and physical preparation experts would have a deeper insight into how athletes perform landing actions, and the specific training required to enhance athlete capability.

Most injuries associated with freestyle athletes are sustained from jump landings or falls/crashes following failed jumps/tricks (Robb, 2014). In freestyle skiers especially, one of the primary concerns for knee injuries during landings is the boot-induced anterior draw mechanism caused by the ski boot when landing in deep knee flexed positions (Flørenes et al., 2012). Freestyle skiers appear to “hang” on the back of their ski boots during deep landings and utilise the stiff ski-boot design to support lower-limb stiffness throughout the landing phase. Of concern, this position inadvertently decreases hamstring activity and increases anterior shear forces acting on the knee and specifically the ACL (Turnbull et al., 2011). Similar, observations of elite freestyle riders in training showed athletes largely adopt a knee dominant, flexed riding posture to maintain board control and generate compliance between the snow boot and the snowboard via the binding mechanism. This also appears to be the strategy riders adopt at jump take-off and landings. Riders flex their knees promoting excessive anterior tibia forward displacement creating high ankle dorsiflexion angles, this in-turn creates an over-reliance on quadricep (Malinzak et al., 2001) muscle groups and a decrease in the total contribution of hamstring muscle force (Renstrom et al., 1986). Consequentially, anterior knee shear force and the potential for ACL loading is increased. In addition, the classic snowboard technique also requires the rear leg (dominant leg) to form knee valgus and hip internal rotation positions, which are well understood to increase knee joint torque and ACL loading (Norcross et al., 2010, Davies et al., 2009, Determan et al., 2010). Numerous studies have linked injury risk with suboptimal limb kinematics and poor motor control during absorption of ground reaction force (GRF) during landings, in the laboratory setting (Norcross et al., 2010, Blackburn et al., 2013, Fox et al., 2017) yet, the discussed techniques adopted by snowboarders are essential movement postures encouraged by coaches in the sport today. It is unclear exactly what knee angle is considered 'excessive' that impacts ACL loading in snowboarders, and exactly what limb kinematic characteristics predispose elite freestyle athletes to knee injuries. This information is absent from the literature.

In review of the available literature to date, no research has been conducted on elite freestyle SS snowboarders in the training environment, nor has there been any attempts to identify the biomechanical demands of freestyle jump landings. For the reasons discussed, investigation into the kinetic and kinematic demands of snowboard SS jump landings would provide the sports coaches and sport scientists with key information effecting athlete preparation for their sport. This would allow improved evidence-based training to support performance and potentially decrease the risk of sport related injuries.

2.5 Biomechanical demands

Investigations examining body load and limb mechanics have assessed demands of the ankle joint complex during snowboard carving to understand the incidence of reported ankle ligamentous and fracture injuries in recreational snowboarders (Abu-Laban, 1991, Davidson and Laliotis, 1996, Bladin et al., 2004). Delorme et al., (2005) assessed ankle motion in 4 recreationally experienced snowboarders during carved turns on a snow-based terrain. They showed ankles are asymmetrically rotated during toe-side and heel-side snowboard turns, were the front (lead leg) ankle is everted, and the back ankle is inverted. Caused by rotation of the upper body toward the nose of the snowboard allowing riders to have more control of the back leg during turns. From the results, they proposed stiffer snowboard boots might reduce ankle rotation and serve as protective aid against talus joint fractures, but not against anterior talo-fibular ligament strain injuries. It should be considered however, that increased boot stiffness would reduce ankle mobility and likely effect the involvement of structures above the ankle joint, such as the knee and hip as seen in skiing, for example (Klous et al., 2014). To understand the impact increased boot stiffness has on knee, hip, trunk and upper-limb motion during riding and jumps, research that examines whole-body limb mechanics during said actions are important for the sport.

Krüger and Edelmann-Nusser (2009) performed a landmark assessment of the ankle joint complex using 1 recreationally experienced snowboarder during a single ‘test run’ in a prepared snow park, in Austria. The subject was fitted with a full body inertial measurement suit (IMS) (Moven, Xsens Technologies, the Netherlands) designed to give a global impression of rider kinematics recorded during a small 8-meter jump in a snow park, based in Austria. The subject was also fitted with a bilateral insole measurement system (T&T Medilogic, Schoenfeld, Germany) consisting of two insoles, two amplifiers, a wireless data transmission unit, and a data logger, which was fitted into a backpack worn by the snowboarder. Authors found during sloped jump landings that the rear leg of the rider was exposed to 3020 Newton (N) force in a short loading time of 0.1 seconds, whilst in 25 degrees of ankle dorsiflexion and 8 degrees external-rotation. This data has been compared to studies by Boon et al. (2001) and Funk et al. (2003) who showed loads of 2500 N applied with dynamic eversion and inversion actions 48-62 degrees caused fractures in 9 out of 10 cadaveric leg specimens. Similar load values are reported by McAlpine and Kersting (2009) who found vertical external loads of 3521N and 2496N sustained to 2 subjects during landing impacts on a snowboard. It was reported that subjects landed in ankle inversion and moved into further inversion and dorsiflexion of the rear leg during the landing phase of a jump.

These findings indicate that both the load tolerance and available range of movement of the ankle joint may be important considerations when determining the likelihood of joint or ligamentous injuries sustained from snowboard jump landings (Bladin et al., 2004). Only one study has reported peak knee joint moments (relative to bodyweight) during carved snowboard turns, Krüger et al. (2011) reported 3.91 Nm/kg and 4.54 Nm/kg loads acting on the front and rear leg respectively. This confirms the majority of joint loading occurs on the rear leg during snowboard carved turns. It is therefore essential that studies are now conducted on elite freestyle snowboard athletes in the training environment to discover joint loading demands during jump landings in the elite population.

While the aforementioned studies provide insights for snowboard carving and a demands of a single jump, no studies have investigated activity demands of professional freestyle snowboard athletes. Turnbull et al. (2011) provided an in-depth (although unvalidated) discussion about the kinetics and kinematics of landings in the HP. In summary, they noted a positive correlation between the height of each trick and the resulting kinetic energy (mass x velocity) riders experience on landing. Riders will, however land on a sloped surface, which reduces the normal landing forces compared to a flat landing surface (Determan et al., 2010). The magnitude of impact forces experienced are dependent upon the amount of absorption performed by the lower-limbs, how compact the snow is, gradient of the landing slope and rider fall line, and also the horizontal velocity of the rider prior to impact. An optimal landing will occur high on the eccentric wall and will involve a high degrees of muscle stiffness to maximise the transfer of gravitational potential energy to kinetic energy of the rider. Frederick et al. (2006) reported loads of 4-5 times body weight during flat landings from a skateboard Ollie with a jump height of less than 0.5m. Whilst differences between body peak GRF during flat and sloped snowboard landings are currently absent from the literature, identifying load differences in these scenarios would help distinguish load demands placed on elite freestyle athletes training in snow parks and in competition.

Based on the reported information, it is clear load demands seen during flat and sloped landings produce GRF loads which substantially exceed the body mass of investigated subjects. This insight presents a genuine injury threat and concern to elite freestyle athletes regularly training in snow parks and competing on kickers (jumps) ranging 15-25 meters in size. Anecdotally, athletes who are physically unprepared to tolerate landing impacts suffer joint compressive injuries from landings of a high amplitude. No information is currently available that explains the nature or range of forces involved during landings from freestyle aerial manoeuvres. Information about rider peak GRF's is essential to understand load demands placed on elite SS snowboarders. It is now essential to translate this research into freestyle snowsport to discover kinematic and kinetic demands placed on freestyle SS riders and discuss how this information could be useful to athletes and coaches in the applied setting.

2.6 Snowboard jump landing demands

Much of our understanding about the jump landing demands in freestyle snowsport has been derived from research in Alpine Skiing and other aerial based sports like Gymnastics. For example, in Alpine Skiing, studies have shown that the predominant muscle forces are eccentric in nature (Berg et al., 1995b). It is well known that quadricep and hamstring muscle groups have particular importance during the jump and landing phase, with differing activation loads reported to effect the external abduction moments at the knee (Lloyd and Buchanan, 2001) which contribute to anterior cruciate ligament (ACL) injury. The extent of muscular contribution during freestyle snowboard landings however, has not been investigated. From observation, HP and SS riders move into unique landing postures which are held for longer durations compared to alpine skiers. In particular, aerial jumps incorporating spins and corked tricks likely increase the rotational landing forces acting about the body. During landings, riders dynamically load into twisted and flexed spinal postures that significantly increase spinal load (Yamakawa et al., 2001). Extreme ranges of motion occurring at the spine are usually associated with forceful ankle pronation and knee valgus positions to achieve pressure and torsion on the board for effective board control during landing and takeoff (Turnbull et al., 2011). Attempts to maximise landings by manipulating body position into extreme range, under rapid deceleration moments is likely to increase the overall contribution of musculoskeletal tissues in response to three-dimensional (3D) GRF's during sloped landings. This may see riders maintain joint loaded positions at extreme ranges of motion for lengthy periods of time in effort to stabilise and avoid falls in landings. Furthermore, differences in muscle activity, limb position and magnitude of GRF's may exist between jumps in regular (straight), switch (irregular), and flat spins. Although, this has not yet been investigated with elite freestyle athletes.

There is substantial research investigating the effect of drop jump height on specific muscle activity during landings from plyometric jumps, showing with increasing jump height from 20-60cm yields differing activation of the quadricep and hamstring muscle groups in drop jump landings. With increasing drop-heights, the activation of quadricep muscles increase, whereas activity of the hamstrings specifically Bicep Femoris (BF) was similar throughout all drop heights (Peng et al., 2011, De Britto et al., 2014). Adequate co-contraction of knee extensor (quadricep) and flexor (hamstring) muscles are understood to balance forces acting on the knee joint, compressing the joint to control high knee flexion/extension and abduction torques immediately after ground contact. Were decreased activation of the hamstring to quadricep ratio may alter dynamic knee stability and may increase risk of ACL injury (Hewett et al., 1996, Hewett et al., 2005). Presently, no information is available indicating the magnitude of maximal voluntary contraction (MVC) seen by elite SS riders during different jump landing heights or tasks performed in snow-based training sessions. Nor are there any validated, evidence-based recommendations regarding trained muscular or mechanical strategies to augment landing performance during snowboard landing tasks. Considering the scarcity of evidence surrounding the biomechanical demands of elite SS athletes in training, research is needed to provide understanding about the physical demands of jump landing movements performed in the sport.

Resistance training, administered through a well-designed training programme, could be used to enhance intra and inter-muscular coordinative ability, as well as maximal isometric and eccentric strength to sustain the magnitude of forces during riding and jump landing actions (Turnbull et al., 2011). Although, it is currently unknown how absolute leg strength may influence the ability to tolerate GRF from high landings. Based on the positive relationship between muscular strength, neuromuscular capacity and the positive relationship with jump landing performance, combining sport specific coordination training with high load resistance training would enhance neuromuscular capacities in freestyle snowboard athletes (Secomb et al., 2015, Secomb et al., 2016). Identifying the exact muscular activity, load demands and movement behavior during SS snowboard jump landings, would enable coaches and practitioners to improve upon current generic training recommendations administered to elite freestyle athletes. This advancement could potentially increase athletic capacity and reduce the prevalence of injuries sustained in landings from poor athletic preparation. It is therefore essential to investigate the biomechanical demands of freestyle jump landings to bring evidence to this area.

Whilst the aforementioned studies provide some insight into activity demands during snowboard carving and a single recorded jump, no peer reviewed research has investigated the biomechanical demands of professional SS athletes in training. Knowledge of the total muscular and joint demands during aerial jump landings is paramount to grow understanding of the physical capacities required to perform jump landings in the sport. Were the significance of error and injuries are most severe during landings (Frederick et al., 2006, Hewett et al., 1996, Turnbull et al., 2011) and in particular, knee joint injuries sustained in training and competition are more significant than any other reported injury.

2.6.1 Quantifying snowboard jump landings

To date, advancements in microtechnology have enabled scientists to measure aspects of aerial manoeuvres, global movement kinematics and joint load kinetics during snowboard jumps. For example, total air-time and average degree of rotation values were investigated in elite HP athletes in training (Harding et al., 2008) and during staged competition (Harding and James, 2010). In the 2008 study, ten HP riders wore a body mounted tri-axial accelerometer (100 Hz ± 6 g) with a tri-axial rate gyroscope (100 Hz ± 1200 deg/s) and video footage panning each HP run was collected using a Sony 3CCD 50 Hz digital video camera. Data integration by a summation technique proved successful identifying acrobatic rotation of riders performing 180, 360 degree (deg), 540 and 720 degrees of rotation, in a single axis. Although, the same method was not successful in identifying athlete rotation across three-axis at one time, and therefore lacked specificity to identify typical off-axis acrobatic maneuvers in HP and SS training and competition. This study did not make reference to the involved landing forces or describe differences in athlete landing strategy during filmed landings. This information is still absent from the scientific literature.

2.6.2 Quantifying joint kinematics

The research to date has investigated 3D joint kinematics in skiing and snowboard carved turns in the field (Delorme et al., 2005, Kurpiers et al., 2009, Krüger et al., 2011, Klous et al., 2012, Klous et al., 2014, Kondo et al., 2014) although, just two studies have presented data from non-elite subjects in snow-based environments (McAlpine and Kersting, 2006, Krüger and Edelmann-Nusser, 2009). The four high speed camera SIMI motion system (Unterschleisshelim, Germany) used by McAlpine and Kersting (2006) enabled data capture in a fixed volume 3 x 1.5 x 1.5

meters. To calibrate the volume of space for data capture, authors used a wand-cube technique (motion analysis corporation, Santa Rosa, USA) which increased accuracy through a reduction of maximum absolute errors. This method proved superior to the standard cube calibration technique and is a reliable method for testing kinematics in future investigations. Moreover, the full body IMS (Moven, Xsens technologies, Enschede, The Netherlands) used in the Krüger and Edelmann-Nusser (2009) study has an advantage over the optical camera method in terms of capture volume, measurement preparation, and analysis time. For these reasons, the full body IMS has also gained popularity with other investigations (Harding et al., 2008, Brodie et al., 2008, Krüger et al., 2011) and has since become commercially available. Although, despite the IMS advantages for use in the applied setting, the total net weight of the suit including data loggers amounted to 2.2 kg, which is an additional weight cost to the rider and would likely contribute to increased impact loads upon landing, and potentially increase injury risk. Further development of this technology is required to enable data capture of freestyle athletes without restrictions during aerial maneuvers.

2.6.3 Quantifying joint kinetics

So far, there are just two peer reviewed studies to present kinetic findings during snowboard jumps and aerial maneuvers. McAlpine and Kersting (2009) used two snowboard mounted force platforms situated underneath each binding, with six unidirectional force transducers. The prototype measured 40 mm thick with a mass of 2kg. These amendments would significantly impact a rider’s board control and freedom of normal movement in aerial tasks, which questions the authenticity of data presented in this study for elite populations. Authors noted a concern for increased injury risk using this technology in normal conditions and so opted to restrict the scope of their investigation to a straight forward jump landing. Refinement of this technique is required to assess aerial tasks in future investigations. Later, research by Krüger and Edelmann-Nusser (2009) used a bilateral insole measurement system (T&T Medilogic, Germany) with 120 Hz to detect GRF during a 360 deg indie grab, during a single test run in a prepared snowboard park. The insole measurement system was able to detect peak take-off (930 newton [N]) and (3020 N) peak landing forces, however the accuracy of the measurement system is limited with a root mean square error of 28% (± 6.6%) with reference to a force plate. Given the lack of validity found, the reported data should be considered as an estimate and not true representation of load demands during freestyle snowboard jump landings.

In view of the weaknesses discussed with the aforementioned technologies, an alternative, non-intrusive method should be considered for examination of aerial based maneuvers. Currently absent from the snowboard literature is the use of a tri-axial accelerometer unit to measure jump landing impacts. Accelerometers have previously been used in the assessment of joint loading (Tran et al., 2010) and have also gained popularity in team sports due to their ease of use and advantage to measure athletes without concern of restriction to normal movement. Typical “off the shelf” devices used in team sport settings generally sample data at lower frequencies (100Hz) than laboratory setting devices (1500-3000Hz) (Zhang et al., 2008). Therefore, an accelerometer with at least 1500Hz would be required to accurately detect peak accelerations upon landing. Given the gaps in the literature for a valid assessment of GRF in jump landings, a tri-axial accelerometer could be considered for the kinetic assessment of freestyle jump landings in the field.

2.6.3a Assessment of muscle function

EMG analysis is a well-established, reliable method to measure total muscle activity during ballistic landing tasks (Goodwin et al., 1999, McKenzie et al., 2010) with proven sensitivity to detect changes in peak muscle MVC across different landing heights (Peng et al., 2011, De Britto et al., 2014). A plethora of investigations exist reporting the use of electromyography (EMG) measuring muscle activity during jump landings in the lab, across several sports (Walsh et al., 2012, Jordan et al., 2016, Malfait et al., 2016). Although, to date just two EMG studies investigating elite snowsport athletes in the training environment exist. Of note, Virmavirta and Komi (1991) conducted a landmark EMG investigation in the training setting with four elite world class aerial skiers. Authors used a telemetric EMG unit (Medinik AB Model 1C-600) with a gain of 1000 and a band pass frequency of 10-1800 Hz/-3 dB to detect, transmit and receive EMG activity. EMG analysis was conducted on five muscle groups (VM, VL, Gluteal, Tibialis Anterior and Gastrocnemius) of the dominant takeoff leg during a ski jump with no errors noted in data collection. Findings showed mean relative integrated EMG (iEMG) of knee extensor groups were highest during jump take-off, with gluteal and gastrocnemius groups reported highest during the jump landing phase in comparison to other muscle groups. Based on the importance of quadricep to hamstring (Q:H) coactivation, inclusion of knee flexor muscle (hamstring) activity should be assessed in future investigations to provide a comprehensive insight into knee joint and upper-thigh musculoskeletal demands. Further, the assessment of knee joint kinematics should also be considered to support overall assessment of jump landing severity.

Back et al. (2013) assessed one elite alpine snowboarder and one elite snowboard cross athlete perform carved turns on an experimental slope including 24 gates on a giant slalom course. Bilateral muscle groups of the VM, VL and lateral gastrocnemius were assessed with analysis conducted on the best 5 turns from a potential 24. Subjects mean, and peak EMG activity showed outputs relative to each phase of the carved turn; front-side and backside maneuvers. Further, EMG % appeared highest during moments of increased knee flexion. No mention was made to limb kinematics in this investigation. Knee angle and angular velocity measurements would be useful to determine the overall involvement of lower-limb musculature in snowboarding tasks.

2.6.3b. Impact of landing height

The impact of landing height and its relationship on recorded EMG musculature within the literature is clear. Generally, studies report an increase in mean and peak muscle EMG with increasing jump landing heights, with a predominant increase seen in quadricep over hamstring peak muscle activity (Zhang et al., 2000, Zhang et al., 2008, Peng et al., 2011, De Britto et al., 2014, Ford et al., 2011). Commonly, world class freestyle SS courses include jumps ranging 18-23 meters in height, propelling riders up to 30 meters in the air. At a total jump height of 65 meters, Virmavirta and Komi (1991) reported iEMG landing data 8 times the value of relative iEMG jump take-off. Despite the lower amplitudes seen in SS training and contests SS/HP athletes compared to aerial skiing athletes’ ability to absorb very large GRF under rapid loading times is paramount from a performance and injury risk perspective. Based on our understanding of the impulse-momentum relationship, SS riders must create a change in momentum upon landing, with the capacity to rapidly dissipate GRF with a high production of muscle MVC through isometric and eccentric force actions (Turnbull et al., 2011). Short contraction times require high degrees of limb stiffness prior to and upon landing to maintain board control and correct posture preventing a loss of control and potential crashes (Frederick et al., 2006). Presently a working knowledge of neuromuscular demands during snowboard landings from large jump heights in elite freestyle athletes is currently absent from the scientific literature.

2.6.3c. Impact of unstable surface landing

There is a large body of evidence acknowledging the impact of unstable surface landings with drop/fall height, fast and slow plyometric jumps and muscular contraction with reference to the corresponding muscle activity (EMG). Although, to this authors' knowledge studies investigating jump landing assessments in the field have not discussed the impact of unstable and changing snow surfaces and the influence this may have upon the reported GRF, joint kinematics, and/or muscle EMG activity reported. Anecdotally, freestyle snowsport coaches note athletes fall most often due to a sudden loss of balance and become unstable because the ski/board loses ideal contact with the snow during landing. Athletes may "catch an edge" (ski/board edge catches the surface of the snow) which interrupts compliance between ski/board and the snow. Possibly due to bumps, divots and contours in the surface, athletes will attempt to rapidly adjust their body position to regain control, which usually forces a change in arm and trunk posture and a rapid and simultaneous extension at the knee and hip. Clearly then, unstable and changing surfaces are an external, environmental factor that should considered within the context of physical demands.

In a study involving vertical drop landings onto an unstable surface (BOSU ball), subjects whom landed with greater landing apprehension adopted an upright trunk and knee extension posture, which was found to increase lateral hamstring activation and decrease overall quadricep involvement in comparison to stable surface jumps (Shultz et al., 2015). In contrast, Prieske et al. (2013) reported increased GRF during vertical drop jumps onto an unstable surface, but this was not associated with increased muscle EMG activity during the preactivation phase of landings. Moreover, a study assessing subjects performance during depth jumps and countermovement jumps on a sand surface found increased quadricep EMG activity after a period of training (Mirzaei et al., 2013). Authors noted an increase in ankle joint dorsiflexion in conjunction with higher motor unit recruitment and rate of force development in quadriceps placing more tension on the musculoskeletal tissues as subjects attempted to generate tension throughout landing and push off phases. From this, it would appear that a change in muscle activity and GRF is relative to the surface type and jump/landing action. Practitioners and researchers working with snowsport populations seem to have an awareness that external factors such as the snow is a risk inherent to elite snowsport (Jordan et al., 2017) yet an understanding of how this exactly impacts landing tasks has not been reported in the scientific literature.

2.6.3d. Pre-post contact landing differences

Several researchers have identified impact forces that occur in less than 30-50 milliseconds (ms) as passive impact forces, which imply a rapid response to impact loading from the human skeletal system (DeVita and Skelly, 1992). Ford et al. (2011) showed within the first 100ms of landing, the maximum GRF and estimated peak ACL force typically occur, making this the most hazardous phase of jump landing. In addition, Frederick et al. (2006) reported peak vertical ground reaction force (VGRF) loads during skateboard ollie jump-landing within similar loading frames of 30-80ms. With this in mind, the ability to reduce high impact forces rapidly must suggest there is some preactivation of skeletal tissues prior to the instance of landing. The concept of preactivation is described by a number of texts showing increased muscle preactivation of knee extensors combined with high joint stiffness, to enable stiffer landings (DeVita and Skelly, 1992, De Britto et al., 2014). A stiffer, more upright landing pattern characterised by reduced knee and hip flexion, provides a more hamstring dominant landing strategy during the pre and initial contact loading phase (Blackburn et al., 2013). While increased hamstring activation, in particular medial hamstrings, is considered advantageous to reduce anterior tibial shear force and provide knee joint compression (Blackburn et al., 2013). Research by Walsh et al. (2012) implies proximal anterior tibial shear force, knee valgus and knee rotation moments are all reduced during more knee flexion based landing strategies. Malfait et al. (2016) showed that knee and hip flexed landing patterns are generally accompanied by higher mean and mean peak medial/lateral quadricep and hamstring activation. The same author also found reduced hip flexion angles produced a quadricep dominant strategy during the peak loading phase of landing, with greater peak medial hamstring activity seen prior to landing. Authors suggest preactivation could be explained by the feedforward strategy, which could further explain large increases in quadricep activity found during landing moments in effort to constrain high landing forces. The anticipation of landing is suggested to enhance the tension applied to the musculotendinous structures in the foot, ankle and adjoining structures to assist the dissipation of GRF throughout the phases of landing (Zhang et al., 2000).

Commonly, the amount of hip and knee joint flexion used by snowboarders during landings from a kicker <25m will increase in effort to constrain GRF and maximise high joint stiffness (Turnbull et al., 2011). Increased knee flexion angle prior to landings has been linked with increased ACL injury risk, possibly because of increased landing heights (Zhang et al., 2008). And so, a preferential momentary knee extension prior to landings appears to be an effective strategy to increase knee Q:H coactivation during landing phases and maximise gluteal maximus involvement alongside Q:H muscle activation (Walsh et al., 2012). As pointed out by Zhang et al. (2000), joint specific movement behaviours appear to vary largely in relation to jump height. Ankle and knee contributions appeared greatest during small jumps (<1.0m) which may be more related to the dynamic rails and box jump features performed in SS. In contrast, the contribution of larger, proximal joint structures (knee and hip) increased in conjunction with height (>1.0 m) and increased mechanical loading. Similar to the landing techniques seen by snowboarders transitioning from smaller to bigger jumps, generally the bigger the jump (height), the greater the overall amount hip flexion and flexed body postures are observed on landing. Again, this theory is supported by the work of Walsh et al. (2012), linking increased landing height with higher peak muscle EMG activity, although this insight has not been explored with elite freestyle snowboard athletes to date.

2.6.3e. Differences during three-dimensional landings

While the reviewed evidence provides insight around the biomechanical characteristics of sagittal plane jumping and landing tasks, this offers little significance to the 3D snowboard jump-landing demands. Very few peer reviewed studies have investigated 360 deg rotation jumps and landings. A study by Bai et al. (2011) showed peak timings of EMG activation in hamstrings occurred before peak timing of quadriceps during a standing 360 deg vertical jump landing. Both mean peak quadricep and hamstring activity occurred after initial contact, which coincides with the research discussed here previously. Authors also found medial (semitendinosus) and lateral (bicep femoris) hamstrings acted to prevent valgus knee moments during the 360 deg jump landing. Later, work by Bai and Fukumoto (2013) measured 10 females perform an 180 and 360 degree vertical jumps on the spot, with arms folded. Findings showed earlier hamstring preactivation during the 180 over 360 deg jump landings. And also, earlier timing of medial (SM) and lateral (BF) hamstrings before quadricep muscle groups (VM, RF, VL) in both the 180 and 360 deg conditions. In the quadricep groups alone, preactivation timing tended to be earlier in the 360 deg landing than the 180-degree landing. Moreover, an applied study involving elite roller skaters, reported increased BF, gastrocnemius, VL, RF and GM activation during ‘triple apes’ (3 rotations) during propulsion and flight phases, compared to tricks involving less rotations (Pantoja et al., 2014). The study reported more complex rotational tasks were associated with greater lateral hamstring involvement during the flight phase. While limb kinematics were not reported in this study, it could be suggested that increased preactivation of hamstrings prior to landing is a feedforward mechanism to achieve landing efficacy and motor control in complex landing tasks (Riemann and Lephart, 2002). Because the feedforward mechanism is largely driven by visual feedback about the environment and task, it could be considered that athletes performing complex rotational maneuvers in freestyle snowboarding may exhibit more hamstring preactivation in tricks requiring more rotations. Though this has never been explored with elite snowboard athletes.

A number of publications have cited an improvement in hamstring activation during dynamic stabilisation tasks (including jumping) following windows of focused neuromuscular training (Chimera et al., 2004, Medina et al., 2008, Zebis et al., 2009). Based on the process of neuromuscular adaptation, it could be suggested athletes with greater skill-based experience, and whom perform technical jumping tasks regularly (such as 360 deg landings) may be more capable at achieving better Q:H preactivation and timing of hamstring preactivation during more complex jumping tasks than less experienced individuals. Although, this knowledge is currently missing from the scientific literature.

In review of the discussed, it would appear landing strategies are adopted relative to the perceived landing task and environment. The relationship between the considered EMG literature to freestyle snowboard jump-landings bears little relevance due to a number of factors inherent to the sport, being; landing height, horizontal velocity upon landing, landing with a snowboard strapped to the feet, landing on an angled and unstable/changing surface, and forces acting in 3 planes at one time. The range of factors listed have not been investigated concurrently by any published work in existence. Furthermore, much of the available literature presents findings with non-athletic populations done in the laboratory, which is far removed from the applied freestyle snowsport environment. For these reasons, research must be conducted with elite freestyle athletes in the applied setting to discover the biomechanical demands of jump landings.

2.7 Summary

Professional freestyle SS snowboarding is an acrobatic, skill-based sport, comprising of short-term, explosive jump landing actions which impose extreme physical loading to the body linked to sports injuries. To date, research investigating kinetic and kinematic activity of athletes has shown microtechnology can be used to evaluate aspects of locomotion, joint and muscle kinetics and movement kinematics in the sports environment. Although, no evidence is available that describes the biomechanical demands of snowboard jump landings with elite SS snowboarders in training or competition. Moreover, no studies have attempted to investigate, in combination, landing impact (acceleration), magnitude of muscular activity, and related movement characteristics during jump landing manoeuvres performed regularly in the sport. This information will allow technical and physical preparation coaches to understand the global physical demands placed on athletes following tricks performed regularly in training and competition. Moreover, this information will enable elite athletes and coaches to ensure appropriate steps are taken in the physical preparations for athletes partaking in professional competition to enhance athletic preparation and attempt to reduce risk of landing related injuries. Therefore, this thesis will for the first-time present kinetic, kinematic and muscular demands during jump landings collected from elite British freestyle SS snowboarders during a training session. The knowledge gained from this is unrivalled by any study in this area to date.

2.8 Aims of thesis

The overall aims of this thesis are to investigate the biomechanical demands of professional freestyle snowboarders during jump landing maneuvers on a snowboard. Investigated measures will be collected directly from athletes of the Great Britain (GB) Park and Pipe Team and performed at UK based training centers. Information collected will inform professional coaches of the specific physical demands of snowboard landings, and further provide knowledge currently absent from the scientific literature. These aims will be achieved by specifically addressing the following objectives:

1. To assess the severity of snowboard jump landings completed by an elite SS snowboarder on an artificial dry slope in training. As part of a pilot study, investigated measures will be obtained directly from an elite SS athlete (n=1) conducted during a GB Park and Pipe team training session in the UK (pilot investigation, see methodology).
2. To assess the key biomechanical (kinetic, kinematic and muscular) demands during landings from a staged drop onto a sloped landing in elite snowboarders. Athletes will perform three specific landings in regular, switch and 360 deg rotation. Investigated measures were obtained directly from elite athletes (n=5) during a GB Park and Pipe team training session, held at a UK indoor snow dome venue.
3. To critically evaluate group and individual differences during pre and post landing phases between the 3 jump landing conditions (regular, switch and 360 deg rotation) utilising the data obtained from these elite snowboard athletes.

2.9 Hypotheses

The following set of hypotheses are drawn based on an understanding of the biomechanical demands relating to drop landings from the reviewed scientific literature:

1. Higher peak resultant board acceleration (g) at initial contact (IC) measured during complex technical landings, in order of; 360 deg rotation (1), switch (2) and regular landing (3). 1 being the largest, and 3 being the smallest. The level of anticipation of the instant of landing (and thus preparation for landing would likely diminish in that order).
2. Greater knee angle and knee angular velocity measured at the point of IC and post-IC moments for the switch and 360 deg landings, compared to the regular landing condition. It is theorized knee angle and angular velocity will increase as the subjects attempt to manage bigger forces from increased rotational landing demands.
3. Higher overall muscle (EMG) activation in post versus pre-IC phase of landing across all 3 landing conditions. And, higher overall pre and post muscle (EMG) activation in switch and 360 deg rotation landings compared to the regular landing condition. It is theorized muscle activation prior to landing would increase as a protective strategy to prevent knee buckling. Also, the athletes are anticipating higher landing severity and therefore will likely activate muscles more after landing.
4. Higher quadricep and hamstring iEMG preactivation during the more technical landing trials, e.g. 360 deg and switch landings compared to the regular landing, as subjects attempt to constrain increased frontal and transverse plane knee joint loading in said conditions.

3.1 Subjects

Data collected in this thesis was taken from elite slopestyle and halfpipe snowboard athletes of the Great Britain (GB) Park and Pipe Team, over two training sessions held at separate locations: 1) pilot investigation; outdoor dry ski slope (Halifax, United Kingdom) and, 2) Main investigation; indoor snowdome facility conducted on an artificial slope (Snow Factor, Braehead, United Kingdom). Each athlete was regarded free of illness, any known injuries and fully available to partake in the planned training sessions. All athletes and coaching staff were informed verbally and in writing about the nature of this study. Written and informed consent was obtained by the coaching staff and snowboard athletes prior to participation and the John Moores University Ethics Committee granted ethical approval. A summary of subject characteristics can be seen in table 1.

Table 1. Mean (±SD) of subject characteristics which participated in this thesis

Study	(N)	Gender	Age (years)	Height (cm)	Body Mass (kg)	Experience Years	Discipline
Pilot (1)	1	Male	19	178	67	12	Slopestyle
Main (2)	5	4 Male, 1 Female	19.6 ± 3.65	173.6 ± 8.20	67.9 ± 8.19	13.0 ± 3.81	Mixed; 4 slopestyle, 1 halfpipe

3.2 Assessment of snowboard jump landings

3.2.1 Familiarisation

All athletes that took part in the investigation regularly attend training at outdoor and indoor snowdome and snow-park facilities and perform jump landing manoeuvres as part of their sport. All testing was conducted as part of a normal team training session, were subjects were selected individually to perform repeat jump landings on selected jump features which differ between each study as outlined here. Detailed instructions were given to all participants, and the assessments were monitored by the lead researcher and the GB Park and Pipe coaching and medical team members.

3.2.2 Developing the methods – pilot investigation

Data collected during the pilot investigation was conducted during a single visit to a GB Park and Pipe team training session which took place on an outdoor artificial dry ski-slope at the Halifax Ski and Snowboard Centre (Halifax, United Kingdom). The study took place in the summer of July 2014, weather conditions were mild with a temperature of 14 Degrees Celsius, and moderate winds. The primary aim of the pilot investigation was to assess the magnitude of landing impacts (acceleration) sustained by an elite male (n=1) slopestyle snowboarder during in a single training session. The secondary aim was to identify if the tri-axial accelerometer was capable to measure snowboard acceleration impact forces during rapid jump landing moments. One male snowboarder was fitted with two tri-axial accelerometers (GPS Viper units) (STATsports, Northern Island) collecting at 100hz. One unit was fitted to the athlete's upper-back using a manufactured STATsport vest, the other was mounted to the centre of the snowboard using adhesive tape (see figure 4). Each GPS viper unit weighed less than 50 grams. The subject completed a self-led, standard snowboard based warm up for 15 minutes, before being instructed to perform five separate jump trials on a single, small sized jump - specifications; height of jump 1.5 meters, length of run prior to take-off 25 meters, amplitude achieved; around 3.9 meters (see Figure 5). Of the five jumps, four jumps were completed in regular jump-landings (straight air take-off and landing), and one 360 deg front-side jump landing (regular take-off, 360 deg front side flat spin, landing in regular). Each jump was interspersed by 2-3 minutes rest. Following each jump the subject was asked to provide the primary investigator with subjective verbal feedback in response to the question; “how hard did the landing feel?”. The subject could respond with one of the following answers; “Easy”, “Moderate”, or “Hard”. The information was gathered to compare the subject’s perception of landing severity against the objective peak acceleration data taken from the tri-axial accelerometer.

Figure 4. Tri-axial accelerometer (GPS Viper unit) mounted to the centre of the snowboard using adhesive tape for the pilot investigation.

Figure 5. Illustration of the jump used during the pilot investigation. Artificial dry ski-slope at the Halifax Ski and Snowboard Centre (Halifax, United Kingdom).

3.2.3 Analysis of the data – pilot investigation

Data recorded by two GPS accelerometer units was downloaded using STATsport software (version 2.7.1.1.57, STATsport, Northern Island) and then exported to Microsoft Excel software package for further analysis. Peak acceleration values recorded during the landing phase, along with subjective feedback after each landing was collected for all five snowboard jump landings, which can be seen in Figure 6. Peak vertical acceleration captured by the snowboard accelerometer ranged 25.5–30.5g. Accelerometer values recorded by an accelerometer worn inside a vest and located on the upper-back were comparably smaller, ranging 4.9–9g. On review, there was no clear relationship between acceleration values recorded by the snowboard and the upper-back. Interestingly, there appeared to be some association between accelerations recorded by the upper-back (accelerometer) and the subjective rating of landing severity. High and low peak acceleration values corresponded with high and low subjective rating to landing severity. Based on this, it is possible accelerations measured at the upper-body may serve as an assessment to indicate jump landing severity. In addition, this finding also coincides with evidence in the literature which has found the trunk/upper-body to play a significant role in energy absorption during jump landing tasks which supports lower-limb performance in said tasks (Kulas et al., 2008, Iida et al., 2012). Future studies should look to assess upper-limb involvement alongside the lower-limbs during snowboard jump landing tasks.

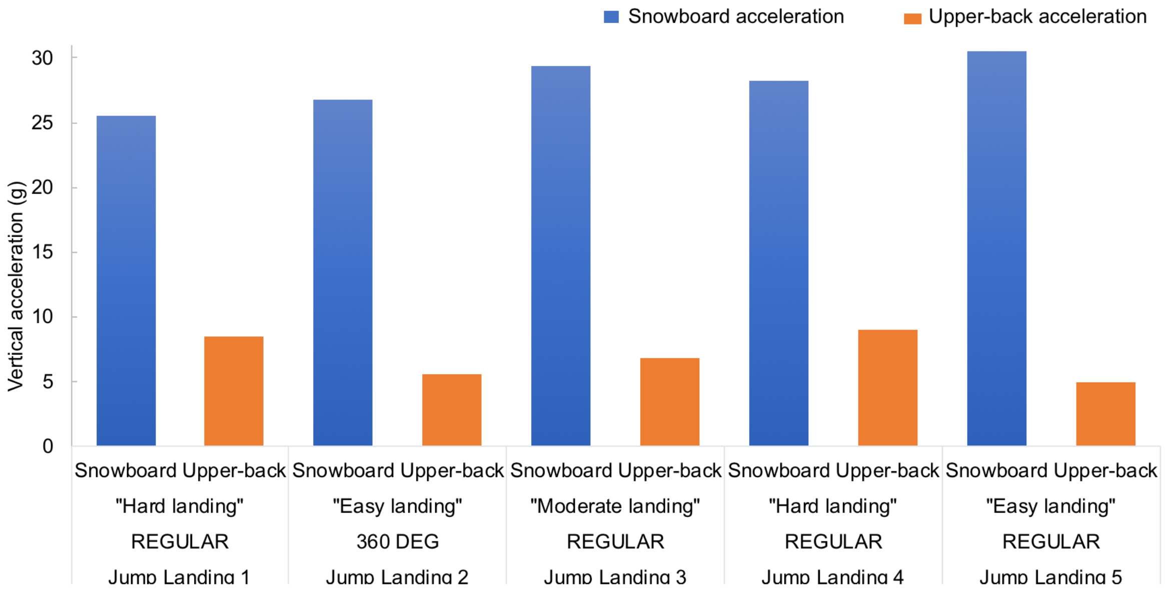

Figure 6. Peak vertical acceleration taken during the landing phase, measured by two tri-axial GPS accelerometers fitted to the snowboard and upper-back during five individual jump landings. Includes subjective perception to landing severity for each landing.

The GPS tri-axial accelerometers provided an insight into peak vertical acceleration during the landing phase (moment when the snowboard made initial contact with the ski-slope). Analysis of the raw data showed that the unit specification was not high enough to capture a complete signal to accurately represent landing acceleration during snowboard jump landings. Figure 7 illustrates a wave curve acceleration signal of 100Hz sampling rate, with an amplifier band setting of 10Hz which was too low for the maximum frequency in trials resulting in aliasing effects (Konrad, 2006). Based on this, a decision was made to employ an accelerometer with at least 1500Hz sampling capacity for the main investigation.

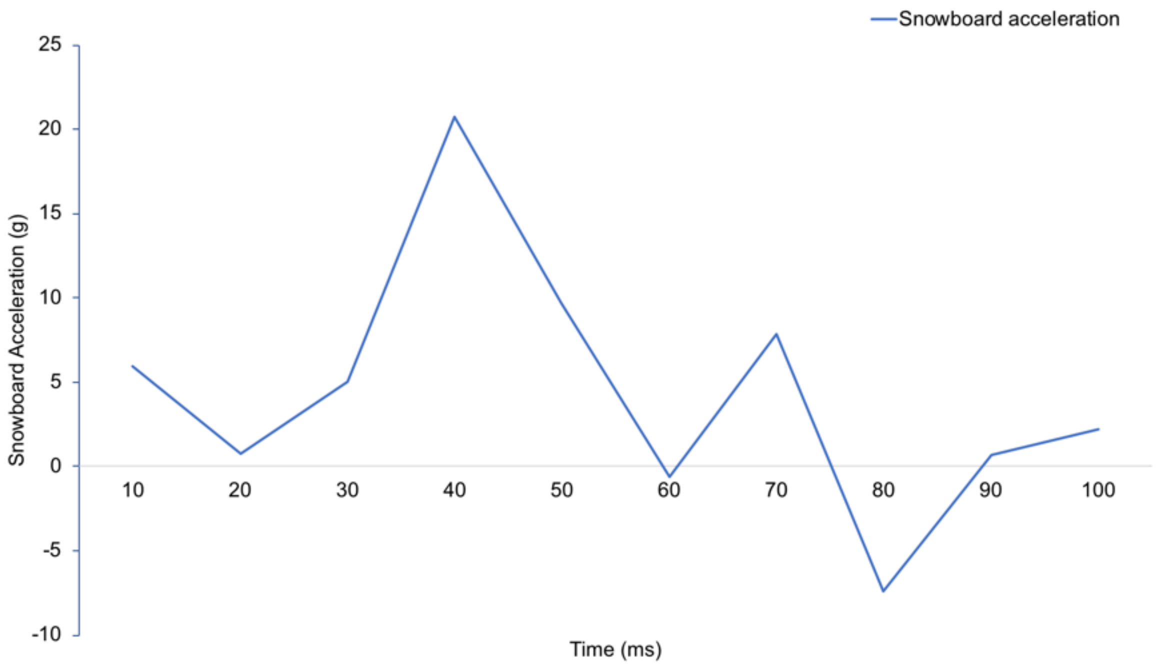

Figure 7. Peak acceleration(g) during single snowboard jump landing on outdoor artificial dry-ski slope (pilot). Shows a wave curve taken from a 100 Hz tri-axial accelerometer mounted to a snowboard; 10 data points captured within 100ms during landing phase (n=1).

3.2.4 Design of an artificial landing slope

Jump landings recorded in the main investigation were performed on a specially designed landing slope, constructed of artificial snow and was situated on the training slope of an indoor snowdome facility (see Figure 8). The landing slope was designed by the head snowboarding coach of the GB Park and Pipe team and shaping technicians of the Snow Factor facility. The landing slope dimensions were designed to replicate a ‘steep landing’, comparable to that of a large kicker found on World Cup and Olympic SS. The landing slope dimensions were; length 4.5 meters, height 6.2 meters, width 2 meters. A large scaffold (total height of 15.2 metres) with a wooden drop platform was positioned parallel to the rear of the artificial landing slope. The drop platform allowed athletes to “jump” from the scaffold directly onto the landing slope to enable assessment of a snowboard landing (see Figure 9). Distance from platform to the point of landing (on the slope) was 2.0 meters. The scaffold and landing ramp provided consistency in drop height, distance to landing and jump angle between athletes across jump landing trials.

Figure 8. Illustration of the artificial landing slope, including the scaffold structure and motion capture cameras situated around the landing slope.

Figure 8. Illustration of a subject jumping off the wooden drop platform from the scaffold onto the artificial landing slope (distance 2.0 metres) during one of the landing trials.

3.2.5 Protocol

Out of the 5 subjects tested, the 4 male athletes performed three types of jump landings consisting of; regular jump landing, a switch jump landing and a 360 deg jump landing (see figure 10). Each subject performed three trials of each jump landing condition. In addition, one female subject also performed three trials of only the regular and switch landing conditions. A regular jump landing required the athletes to land in a regular stance, with their left foot leading on the snowboard. In contrast the switch landing describes athletes landed on the landing slope with their right foot leading. The 360 deg jump landing meant athletes rotated 360 deg in the air prior to landing on the with their left foot leading (regular stance). The start of the jump landing was initiated when the athletes snowboard first made contact with the landing slope, and the end of the jump landing was determined when the athletes completed the landing by arriving at the foot of the landing slope. Testing was completed during a normal team training session and therefore athletes were already sufficiently warmed up prior to jump testing. Before the jump landing trials commenced, athletes performed a standardised movement sequence that consisted of three squats, three squat-pause-jumps, and three counter-movement jumps. This enabled a standard assessment of muscular activity of the upper-thigh and served as reference to EMG data collection for comparison in the different types of jump landings.

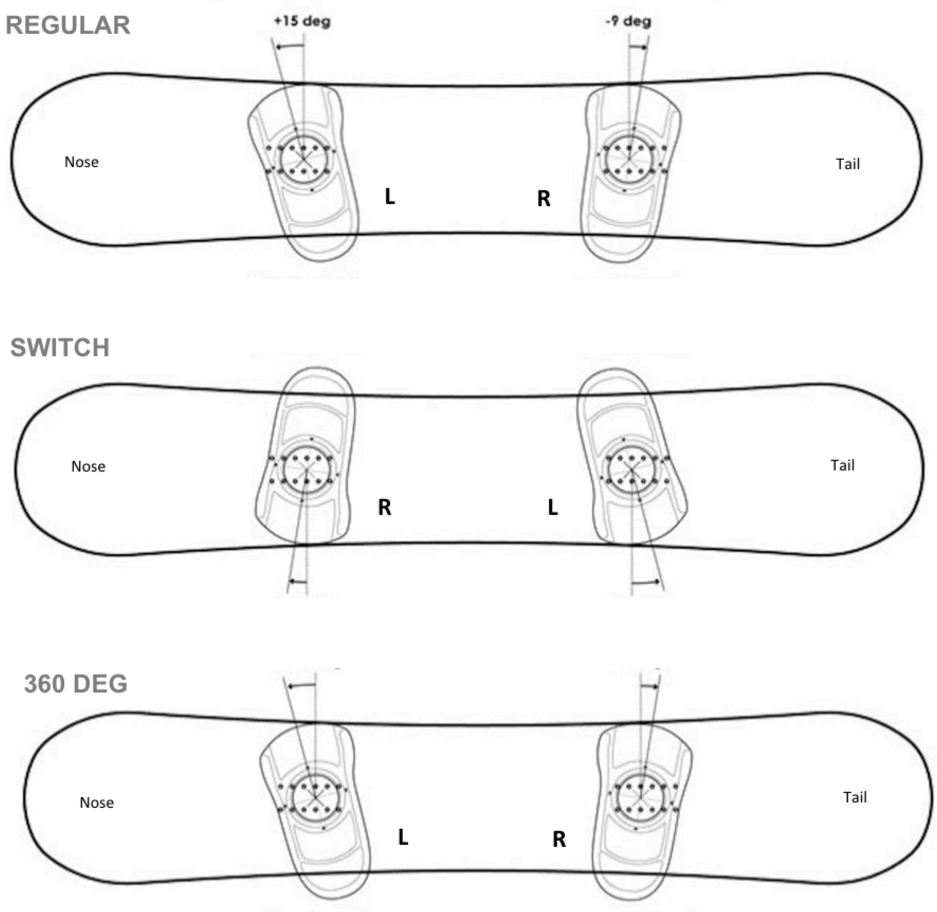

Figure 10. Illustration of the snowboard stances examples investigated during the main investigation: regular, switch and 360d rotation.

3.2.6 Assessment of kinematics and muscle activity

An 8-camera motion capture system (Qqus 300; Qualisys, Gothenburg, Sweden) collecting at 500 Hz was used to record whole body movement for during each landing condition. Retro-reflective markers were attached to each subject, on the following sites; upper and lower sternum, right and left acromioclavicular joint, right and left greater trochanter, right and left on both the medial and lateral knee epicondyles and the right and left medial and lateral ankle malleolus. Markers were also attached on the left and right boots of each subject over first meta tarsal and the heel. Four markers were placed on the front and back of the snowboard near the edges. In addition, a 4-marker plate cluster were attached to the left and right thigh and shanks of each participant (see figure 10). In synchronization with the motion capture system a DTS 3D tri-axial accelerometer (24g, TeleMyo DTS Telemetry system; Noraxon, Scottsdale, AZ) capturing at 1500 Hz was mounted on the center of each subject's snowboard. The accelerometer was attached to the snowboard using strong adhesive tape, with the y axis arranged parallel with the snowboard (see figure 11).

Surface EMG from each subject's vastus medialis, vastus lateralis, rectus femoris, bicep femoris and semimembranosus muscle groups were recorded in each jumping landing using a wireless Noraxon system (TeleMayo DTS Telemetry system, Noraxon, Scottsdale, AZ). The surface EMG data were collected at 1500Hz and was in synchronization with the motion capture and acceleration data. In accordance with SENIAM guideline recommendations, biopolar Ag/AgCI alloy dual surface electrodes (Noraxon Dual EMG electrode) with a spacing of 2 cm were placed on each muscle belly avoiding the innovation muscle sites (Hermens et al., 2000). The surface electrodes were also aligned parallel to the muscle fibres. To reduce skin impedance, each subject's skin was prepared by removing hair with a sterile razor, abrading with sand paper and cleansing the location with an alcohol swab. Placement of electrodes was verified before testing by observing EMG signals as the subjects performed knee extension and flexion actions to activate the involved muscles. Electrodes and wires were secured with elastic tape to reduce sensor movement and were worn under the subject's normal clothing to avoid restriction to movements performed in the trials (see Figure 12).

Figure 9. An example of the reflective marker placement on a subject and snowboard (main investigation).

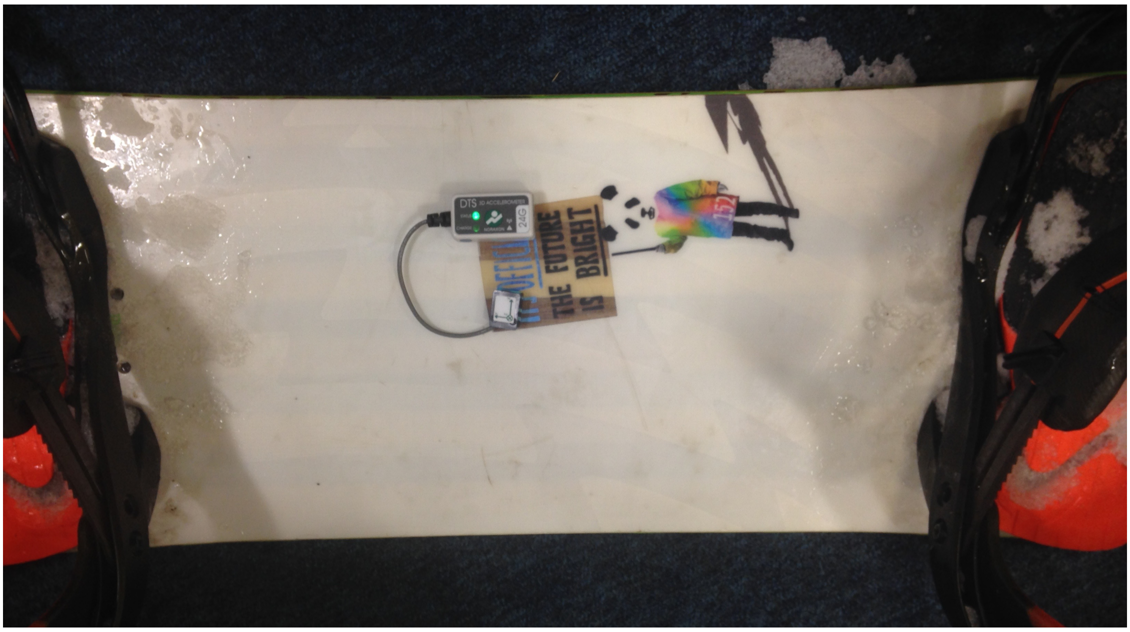

Figure 10. A DTS 3D tri-axial accelerometer mounted on the centre of each subject's snowboard (between the feet).

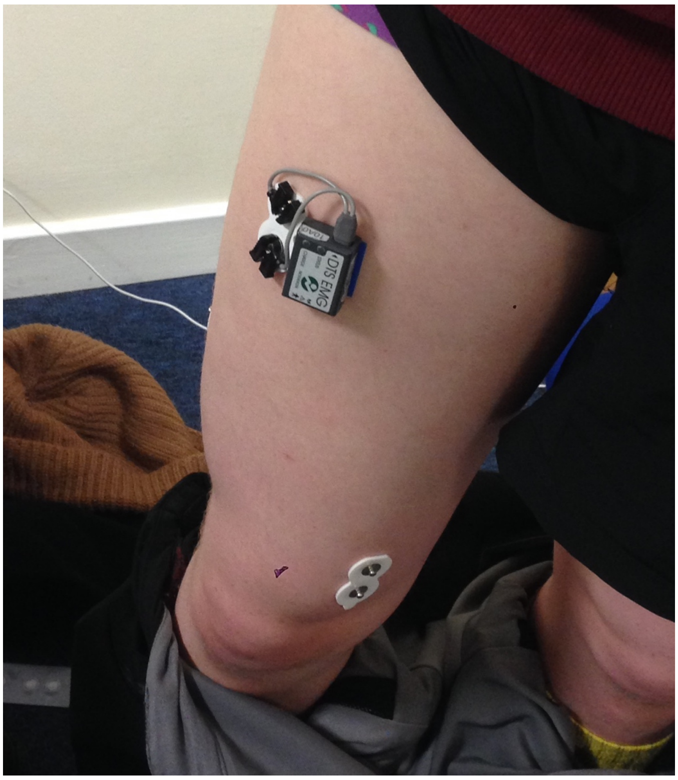

Figure 11. An example of EMG electrodes positioned on the rectus femoris of the upper thigh, on a male subject.

3.2.9 Data analysis

All marker data were labeled and tracked using Qualisys Track Manager Software (Qualisys) and then exported to Visual3D (Version 6; C-Motion, Germantown, MD) for further processing and analysis. A 6DoF body model consisted of a torso, pelvis, left and right thighs, shanks and feet segments. In addition, we also created a snowboard 6DoF segment using markers that were placed on the front and end of the snowboard. Lower extremity 3D joint kinematics joint angles in the sagittal plane (joint angles and joint angular velocities) were calculated using an X-Y-Z Euler angle rotation sequence. Euler sequence represented flexion/extension, abduction/ adduction, and axial rotation. All joint kinematics were represented about a joint coordinate system with the distal relative to the proximal segments (Grood and Suntay, 1983). Segments inertial properties were based on data from Dempster (1955) and represented as geometric volumes (Hanavan and Ernest, 1964). The joint kinematic waveforms for each jump landing trial began with start event of 0.3 seconds prior to initial contact (landing) between the snowboard and the landing slope. The end event occurred 0.4 seconds after the initial contact point. These intervals are similar to the event time points used elsewhere in the literature (Bai and Fukumoto, 2013). Knee joint peak angle was calculated at the moment of landing impact (initial contact).

All analogue signals were adjusted to align EMG, accelerometer and motion data to the moment of impact that occurred between the snowboard and the landing ramp. Raw EMG data was band-pass filtered using a 25 Hz 4^{th} Order High-Pass Butterworth filter, and a 250 Hz 4^{th} order Low Pass Butterworth (BW) filter. After which each EMG was full-wave rectified and then a 0.1 s moving root mean square window algorithm was applied to the EMG data to create a linear envelope. With EMG activity occurring during quiet standing we subtracted this EMG activity from the dynamic trials. EMG data during each jump landing trials were normalised to the maximum EMG amplitude in the countermovement jump (CMJ) trial and represented as a % of maximum muscle activation. Normalised EMG signal was used to calculate the average and peak magnitude for each individual muscle during the preparatory and post-landing (reactive) phases of landing. Mean EMG amplitudes were calculated from the vastus medialis, vastus lateralis, rectus femoris, bicep femoris and semimembranosus during the pre-impact landing phase (pre-IC) and the post-impact landing phase (post-IC). The pre-impact landing phase is defined by the total activity summed in the 200ms prior to initial contact (landing moment). And the post-impact phase is defined by the total activity summed in the 200ms following initial contact. All mean muscle activations were summed during the pre and post contact landing phases and are represented by iEMG.

Board acceleration data in the X, Y and Z directions first had the bias removed by subtracting the mean signal from the dynamic trials, then a 50 Hz 4^{th} order low-pass BW filter was used to remove any unwanted high frequency noise. Peak resultant accelerations were then calculated from the three linear acceleration components during each landing and then represented in units of g's (dividing by 9.81 m/s^2). This was also used to define the instant of landing for type of jump.

4.1 Group mean landing acceleration

The summed mean integrated EMG (iEMG) and standard deviation (±SD) resultant acceleration for each subject in all trials and conditions is presented in Table 8, Section 4.6. Note, subject 2 did not perform the 360 deg rotation landing trials and therefore this data is absent from the results. Group mean and ±SD resultant acceleration (g) across all 3 trials in the regular, switch and 360 deg rotation jump landing conditions are presented in Figure 13. Showing on average subjects recorded the largest mean peak acceleration values in the regular jump landing condition (21.99g ± 3.02), over the switch (19.91g ± 2.50) and 360 deg rotation (21.96g ± 1.66) conditions.

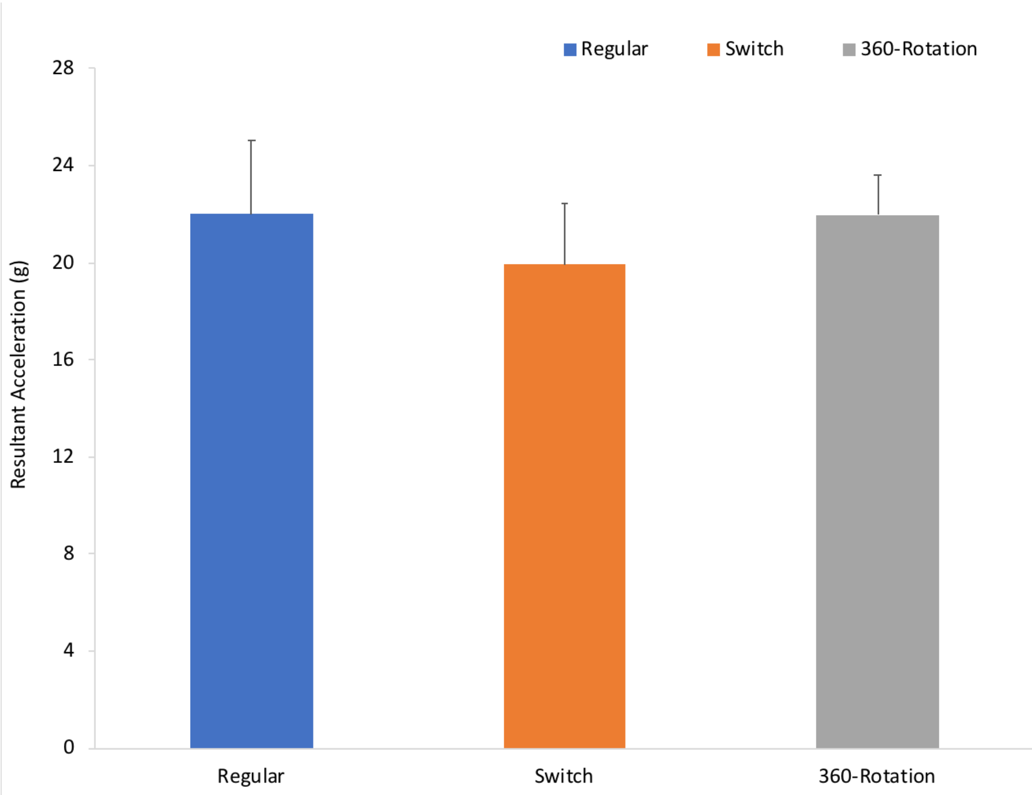

Figure 12. Group mean (±SD) snowboard resultant acceleration (g) recorded during the landing phase for all trials, for all subjects (n=5) during regular, switch and 360 deg rotation jump landing conditions.

4.2 Group mean peak knee angle and knee angular velocity

Knee angle of the lead and rear leg was assessed to examine the peak and change in knee angle between jump landings in the three landing conditions. Due to the difficulty collecting rear leg knee angle (as noted in the methodology) only lead knee angle data is presented here. Mean knee angle data of the lead leg is represented by; 1 subject in the regular condition, 3 subjects in the switch condition, and 3 subjects in the 360 deg rotation condition, which can be seen in Figure 14. In the regular landing condition mean knee angle at the point of initial IC measured 19 degrees (deg) of knee flexion, later increasing to 63 deg of flexion measured during the landing phase of the jump. In contrast, mean knee angle during the switch condition measured 48 deg of knee flexion at IC and increased to 64 deg flexion. The 360 deg rotation landing condition recorded the highest group mean knee flexion angle of 82 deg of flexion and increased to a peak of 88 deg of knee flexion.

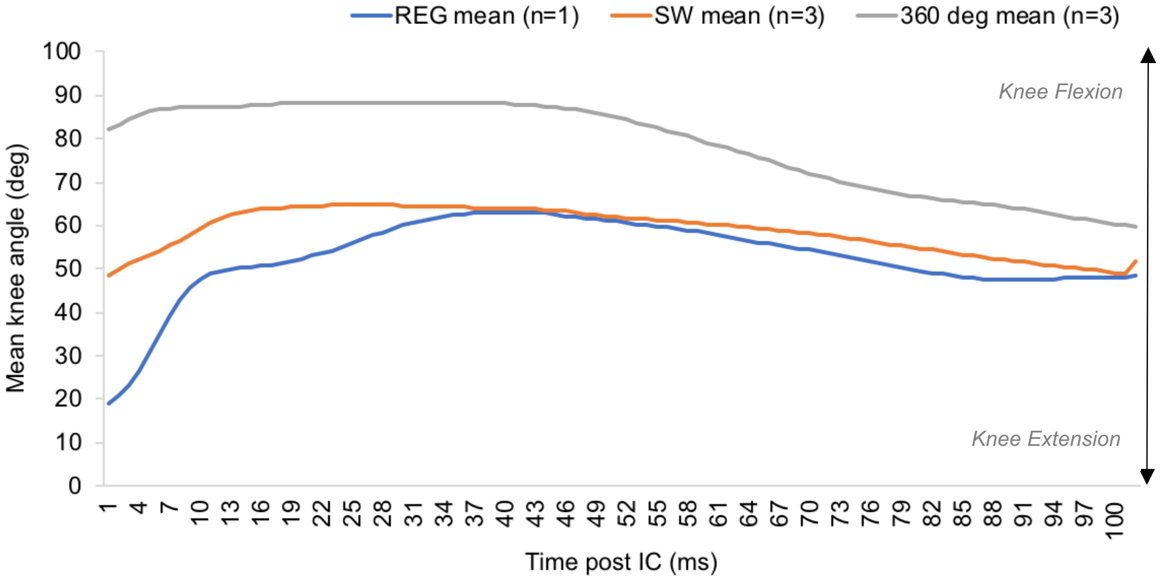

Figure 13. Mean knee angle measured in degrees per second (d/sec) during the post-IC phase of landing for the regular (n=1), switch (n=3) and 360 deg rotation (n=3) during the first 100ms of landing for each type of landing.

Knee angular velocity data presented in Figure 15, shows data for 2 subjects in the switch and 360 deg rotation jump landing conditions. Data in the regular landing condition was not viable for inclusion in this investigation. Group mean knee angular velocity in the switch condition showed the highest magnitude of knee flexion angle measuring 347 degrees per second (deg/s) at the point of IC. In comparison the 360 deg rotation condition showed a similar knee angular velocity of 323 deg/s at IC.

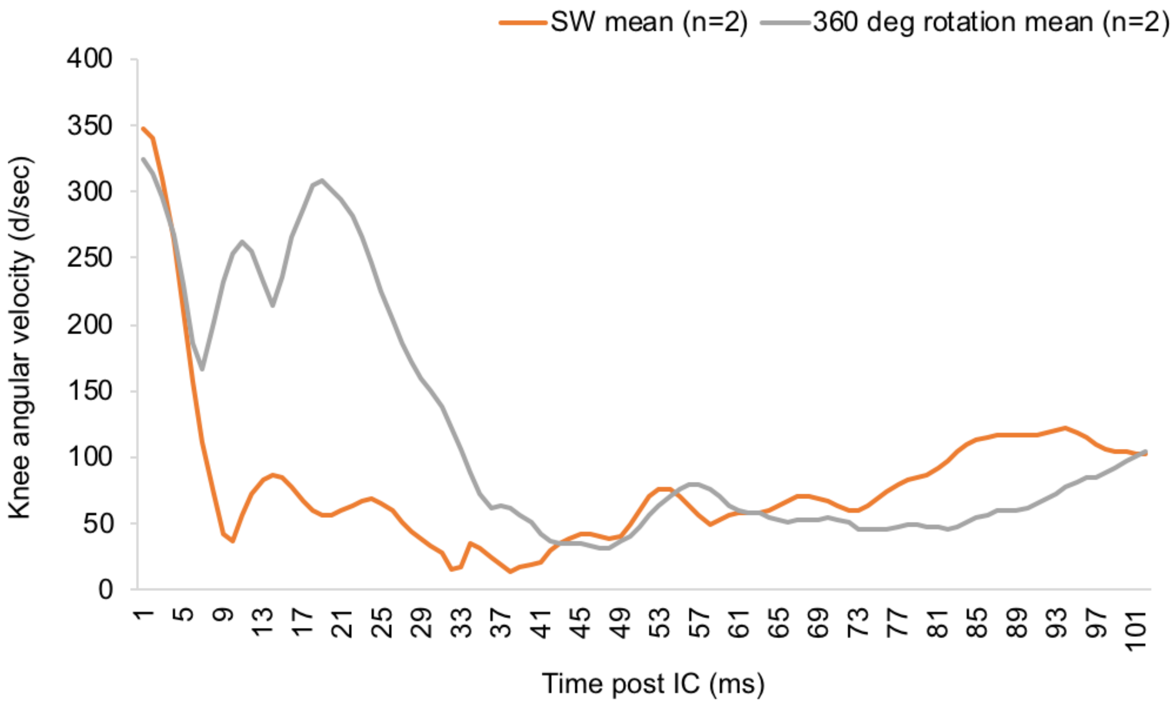

Figure 14. Group mean knee angular velocity measured in degrees per second (deg/s) during the post-IC phase of landing, for the switch (n=2) and 360 deg rotation (n=2) during the first 100ms of landing for each type of landing.

4.3 Group iEMG differences between conditions

On average, subjects produced higher mean summed integrated EMG (iEMG) activity during post-IC landing phase compared to the pre-IC phase of landing in all conditions (see Figures 16, 17 and 18). With exception, higher pre-IC summed mean iEMG values were found in the ST and VL muscles for the regular and switch jump landing conditions only (Figures 16 and 17). iEMG values represent the summed mean of % MVC data obtained against the values found in the CMJ standardisation trials. Peak EMG values for each trial and condition can also be seen in tables 5, 6 and 7 (section 4.6), and are presented as the maximum % of MVC against values found in the CMJ standardisation trials.

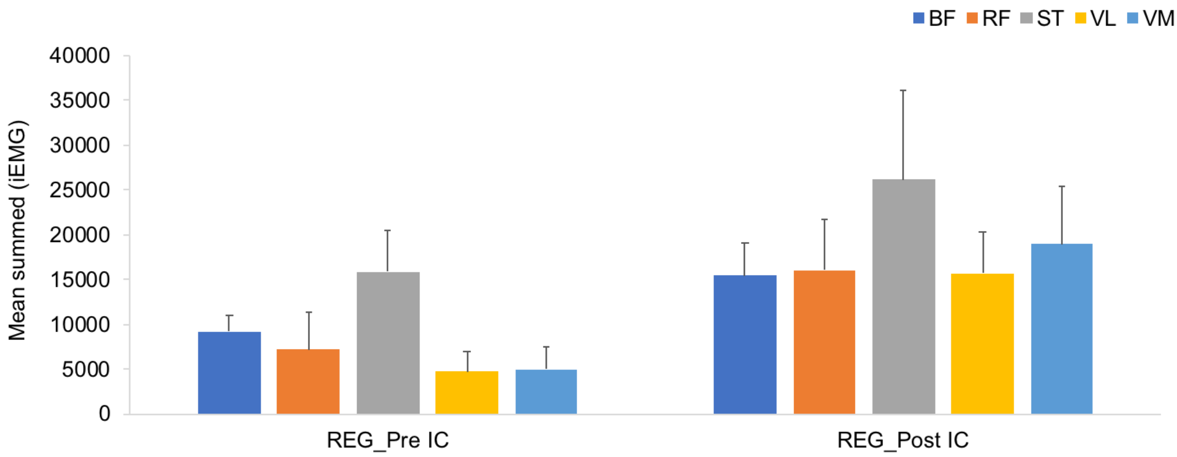

Figure 15. Group summed mean iEMG and (±SD) pre (200 ms) and post (200 ms) IC phase of landing, recorded over 3 trials for the BF, RF, ST, VL and VM muscles in the regular jump landing condition (n=5).

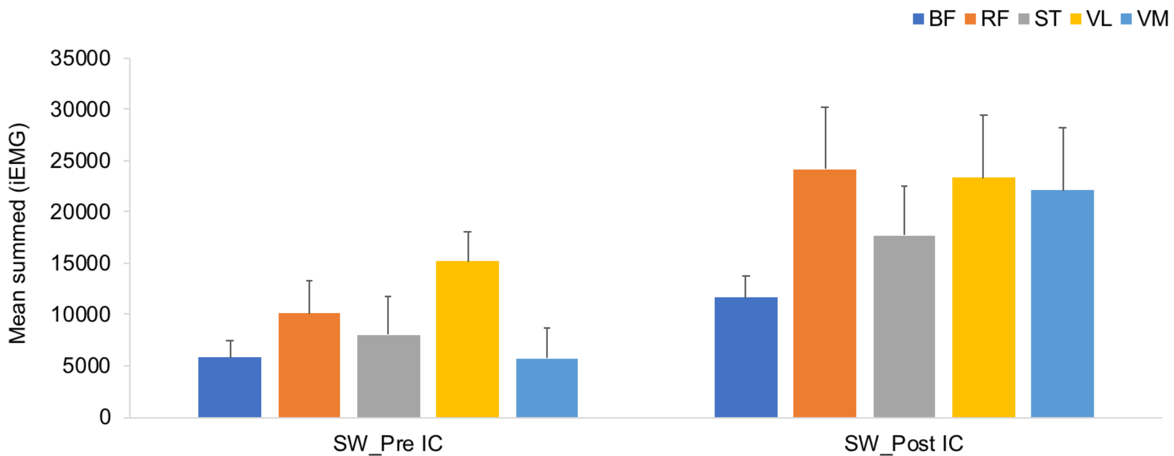

Figure 16. Group summed mean iEMG and (±SD) pre (200 ms) and post (200 ms) IC phase of landing, recorded over 3 trials for the BF, RF, ST, VL and VM muscles in the switch jump landing condition (n=5).

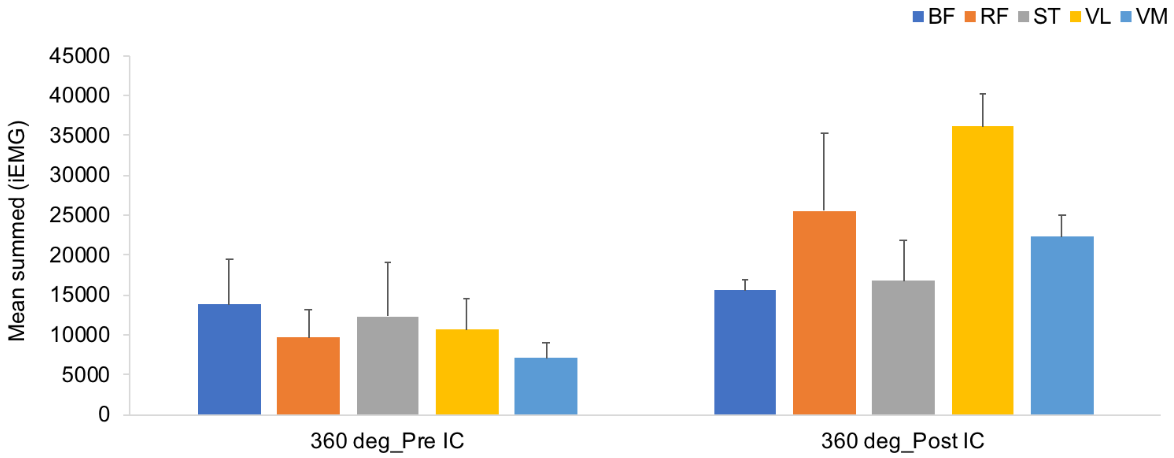

Figure 17. Group summed mean iEMG and (±SD) pre (200 ms) and post (200 ms) IC phase of landing, recorded over 3 trials for the BF, RF, ST, VL and VM muscles in the 360 deg rotation jump landing condition (n=4).

Group mean summed iEMG and SD± recorded in the involved muscle groups (BF, RF, ST, VL, VM) for regular, switch and 360 deg landing conditions can be seen in Figures 19 and 20. Findings between conditions revealed some consistencies in muscle iEMG activity for subjects. Of note, the BF was most active in the 360 deg rotation pre-IC condition (mean summed iEMG 13821) in comparison to all other muscle groups. In the regular pre-IC condition, the ST muscle recorded the highest summed mean iEMG of 15899, which was substantially higher than all other muscle groups. During the switch pre-IC condition, the VL muscle produced the highest summed mean iEMG of 15196 compared to all muscle groups. During the post-IC phase, group mean summed EMG in the RF, VL and VM groups showed a progressive increase across regular, switch, and 360 deg rotation landings. The VL also demonstrated an exponential increase in post-IC summed mean iEMG from regular (summed mean iEMG 15751) to 360 deg rotation (summed mean iEMG 36122) jump landings. The reverse of this finding was observed by the ST muscle group, were a successive decline was recorded in group summed mean EMG from regular (26138 iEMG), to switch (17701 iEMG) and 360 deg rotation (16757 iEMG) during post-IC phase. The BF demonstrated almost identical summed mean iEMG values for the post-IC in the regular (15414) and 360 deg rotation (15599) conditions, with the lowest mean EMG seen in the switch jump landing (11674).

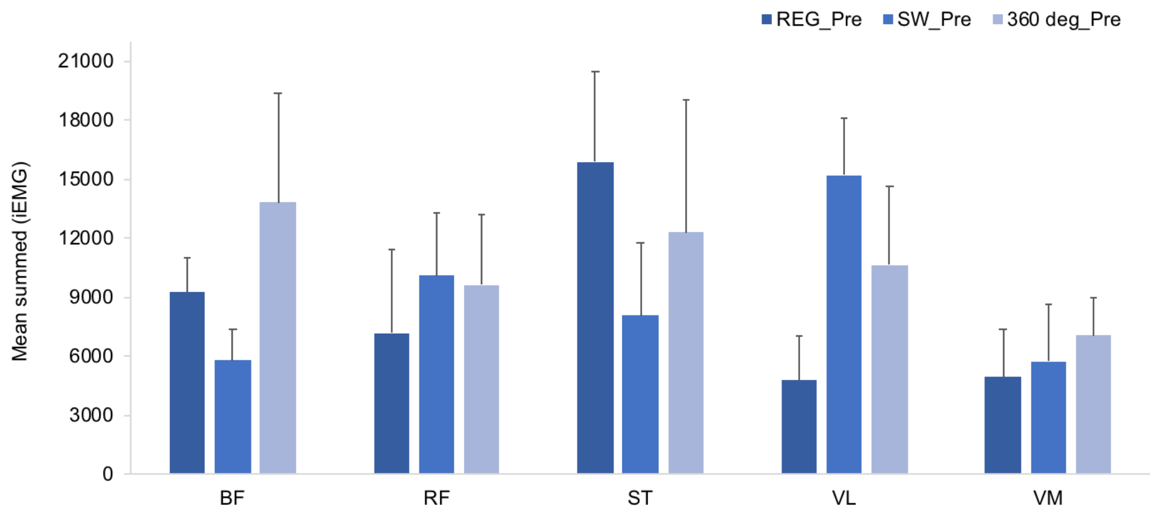

Figure 18. Group mean summed (±SD) iEMG for pre-IC landing phase (200 ms), recorded over 3 trials for BF, RF, ST, VL and VM muscles in regular, switch and 360 deg rotation jump landing conditions for n=4, and regular and switch landings for n=5 .

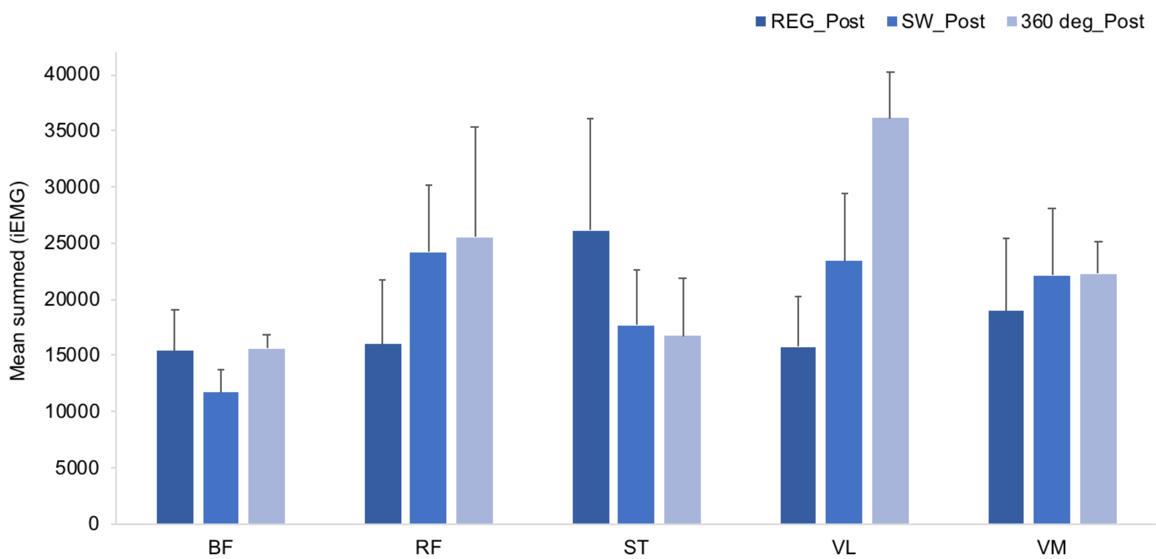

Figure 19. Group mean summed (±SD) iEMG for the post-IC landing phase (200 ms), recorded over 3 trials for BF, RF, ST, VL and VM muscles in regular, switch and 360 deg rotation jump landing conditions for n=4, and regular and switch landings for n=5 .

4.4 Differences between pre-IC and post-IC phases of landing

Findings between subjects showed a high variability of summed mean iEMG activity pre and post-IC phase of landing, which can be seen in tables 2, 3 and 4. This finding was consistent across regular, switch and 360 deg rotation landing conditions, indicating muscle activity is highly variable to each subject. Figures 21, 22 and 23 provides an example of one subjects summed mean iEMG activity during pre and post-IC phases, in the regular, switch and 360 deg rotation landing conditions.

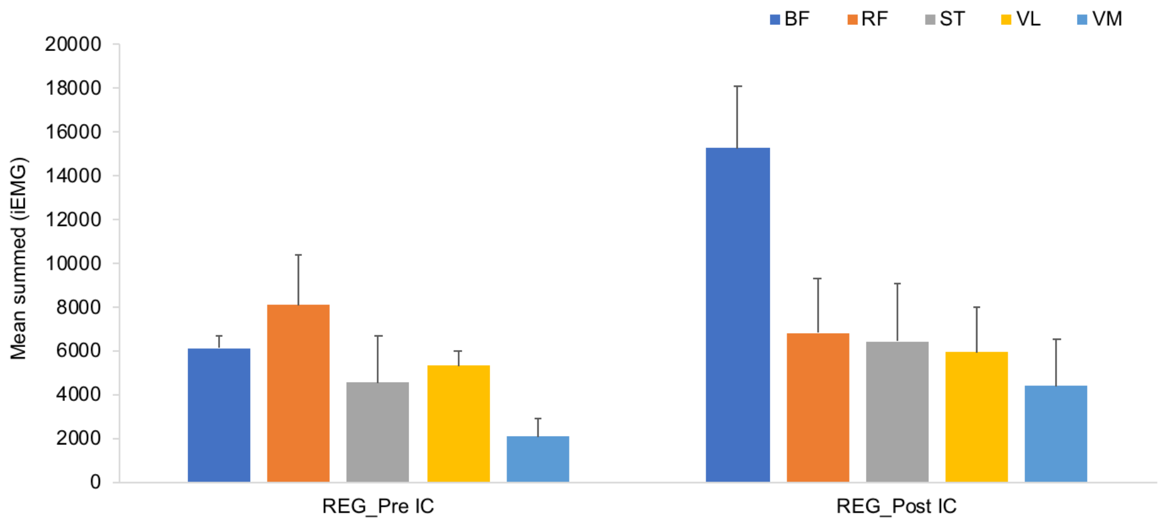

Figure 20. Mean summed iEMG (integrated EMG) (±SD) of the BF, RF, ST, VL and VM; during pre (200 ms) and post (200 ms) IC phases in the regular jump landing condition (n=1).

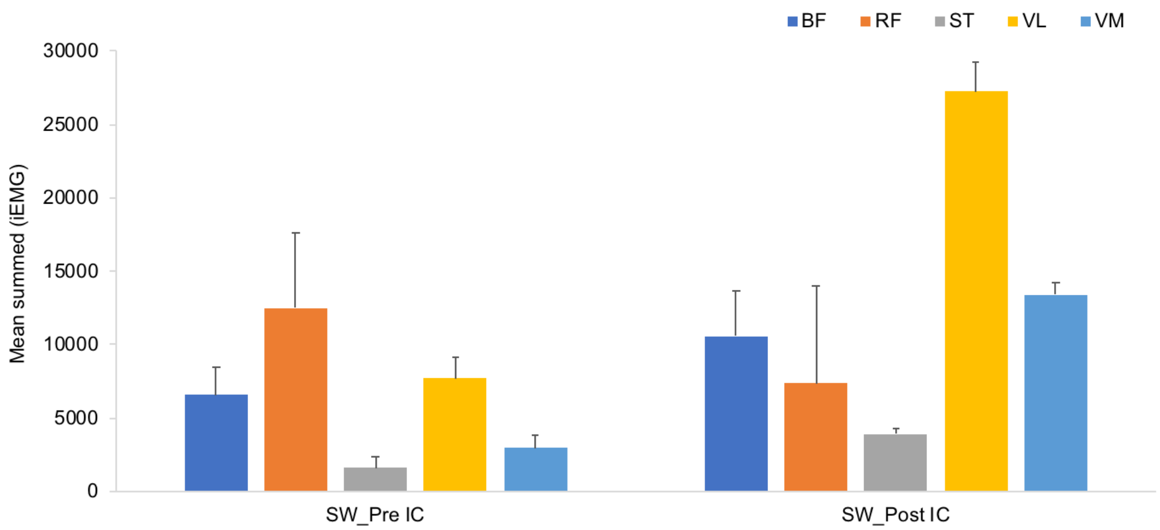

Figure 21. Mean summed iEMG (integrated EMG) (±SD) of the BF, RF, ST, VL and VM, during pre (200 ms) and post (200 ms) IC phases in the switch jump landing condition (n=1).

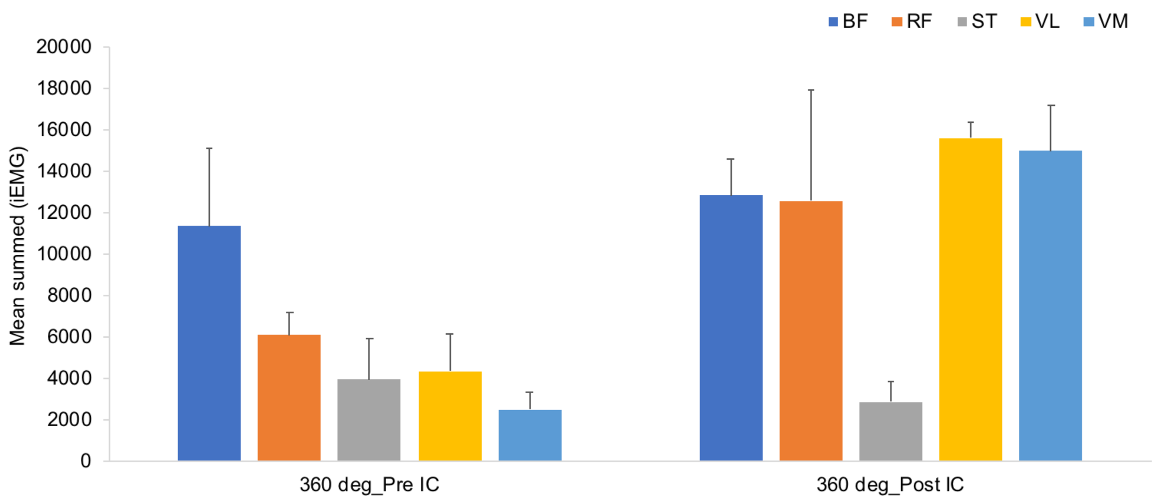

Figure 22. Mean summed iEMG (integrated EMG) (±SD) of the BF, RF, ST, VL, VM, during pre (200 ms) and post (200 ms) IC phases in the 360 deg jump landing condition (n=1).

4.5 Biomechanical findings by subject

Some issues during the assessment of lower-limb kinematics were encountered as noted in the methodology, which has limited the scope of joint kinematic data available for each subject, in particular ankle angle and angular velocity were omitted from analysis. For this reason, knee angle, and were possible knee angular velocity is presented as the primary data set describing lower-limb kinematics at the knee, alongside peak resultant acceleration to illustrate the relationship between landing acceleration and joint kinematics. Figure 24 shows data recorded by subject 1 during the 360 deg rotation post-IC landing phase (200 seconds). Part A shows the maximum peak knee angle occurred in trial 1 at 81.3 deg of the right (lead) leg, mean average peak knee angle measured 76 deg of knee flexion across all trials. The highest peak resultant acceleration was achieved in trial 2 with 24.7g, average resultant acceleration for all 3 trials measured 23g (see part B). Summed mean iEMG measured for the 5 muscle groups of the left (rear) leg displayed varying results across trials; BF (14453) and RF (17965) muscles recorded the highest peak EMG values in trial 2, ST (3954) and VM (17080) in trial 3, and VL (16440) peak EMG was seen trial 1 (part C). Summed mean iEMG for all trials is also presented in part C.

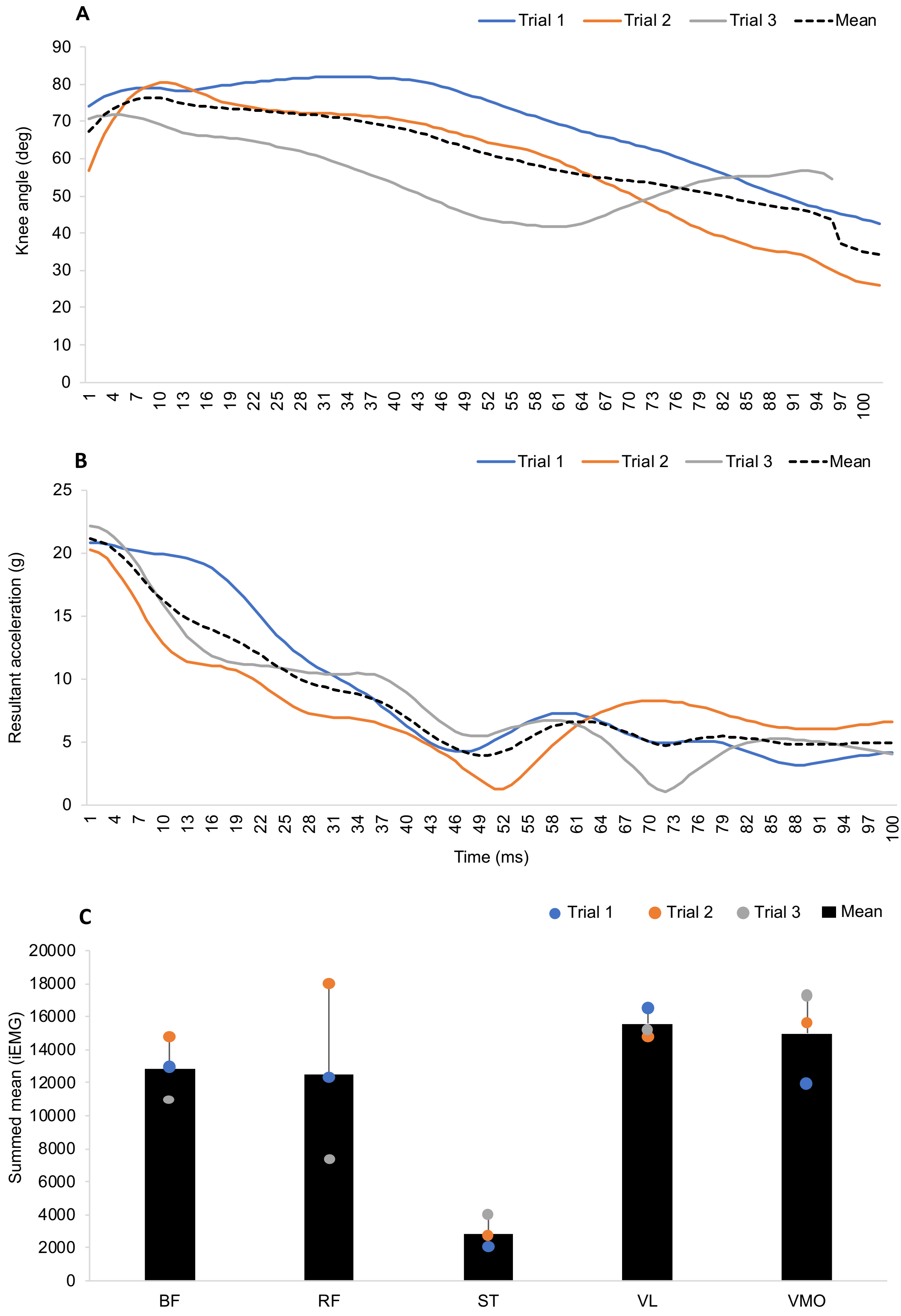

Figure 23. Data recorded post-IC (200 ms) for subject 1 following 3 trials completed in the 360 deg rotation jump landing condition; part A = knee angle (deg), part B = resultant acceleration (g), part C = mean summed iEMG and peak EMG per trial.

Figure 25 displays data recorded for subject 2 over 3 trials in the switch landing condition, in the post-IC landing phase (200 seconds). Part A shows peak knee angle of the right (lead) leg, trial 1 recorded the maximum peak angle at 77.19 deg, mean knee angle across the 3 trials was 61 deg. Part B displays resultant acceleration, peak acceleration occurred in trial 3 at 24.7g with an average resultant acceleration of 22g for the 3 trials. Part C shows summed peak EMG values recorded by the BF (12587), RF (28233), ST (33335) in trial 1. Summed peak EMG recorded by the VL (9431) and VM in trial 3 (12927), and also summed mean iEMG expressed for the 3 trials.

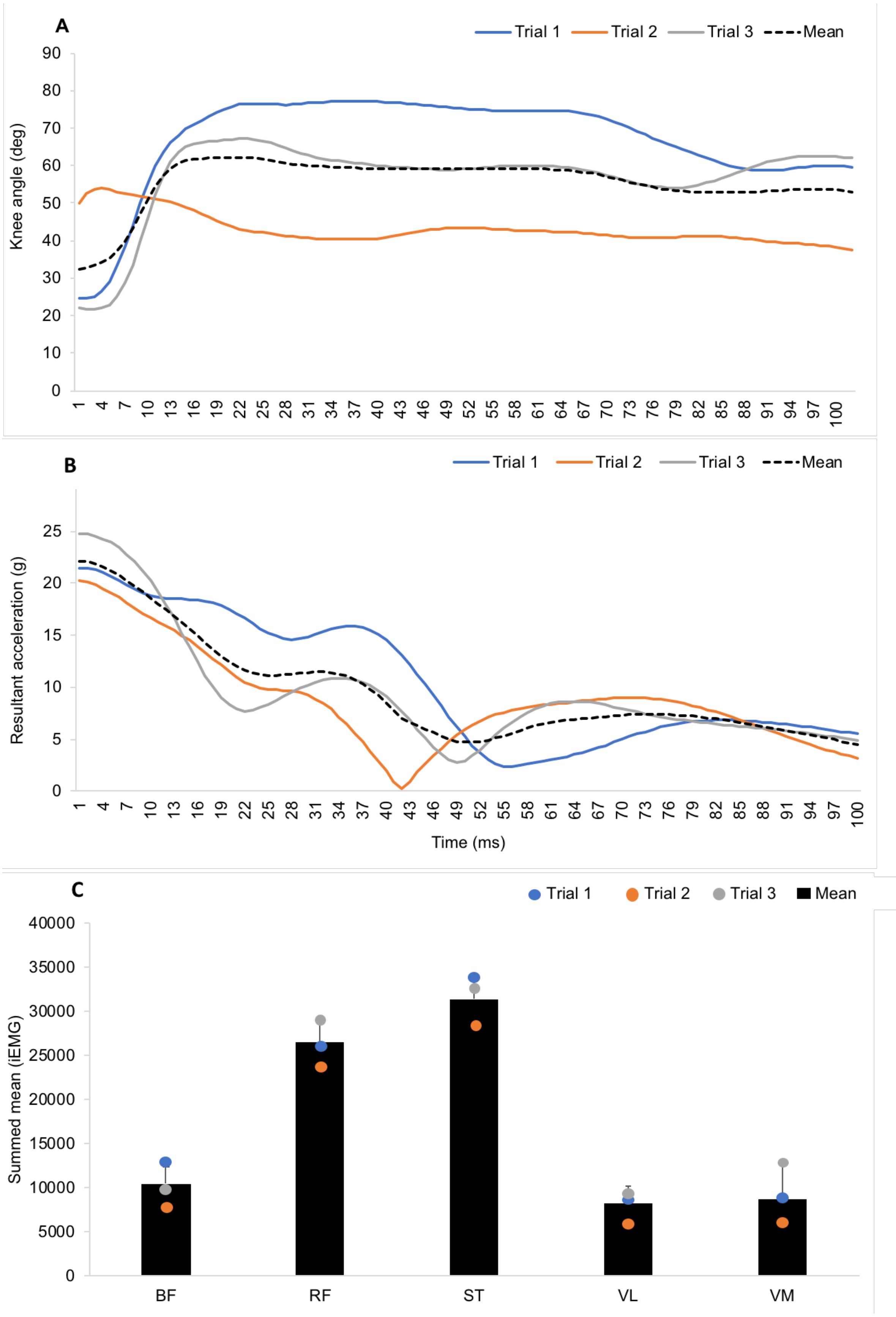

Figure 24. Data recorded post-IC (200 ms) phase of jump landing for subject 2 following 3 trials completed in the switch landing condition; part A = knee angle (deg), part B = resultant acceleration (g), part C = mean summed iEMG and peak EMG per trial.

Figure 26 shows data recorded by subject 3 during the switch post-IC (200 seconds) phase of landing. Knee angle results (part A) of the lead leg show the maximum peak knee angle occurred in trial 1 with 75 deg of knee flexion, mean knee angle for all 3 trials was 64 deg of knee flexion. Peak resultant acceleration (part B) was also recorded in trial 1 with 23.7g, and a mean resultant acceleration of 21.8g for all 3 trials. Peak EMG values found in trial 1 included the BF (10000) and ST (12150) muscle groups. Whereas, peak EMG values for the VL (23325) and VM (5004) were recorded in trial 2, with peak RF (18212) EMG recorded in trial 3. Summed mean iEMG data for all trials is presented in part C.

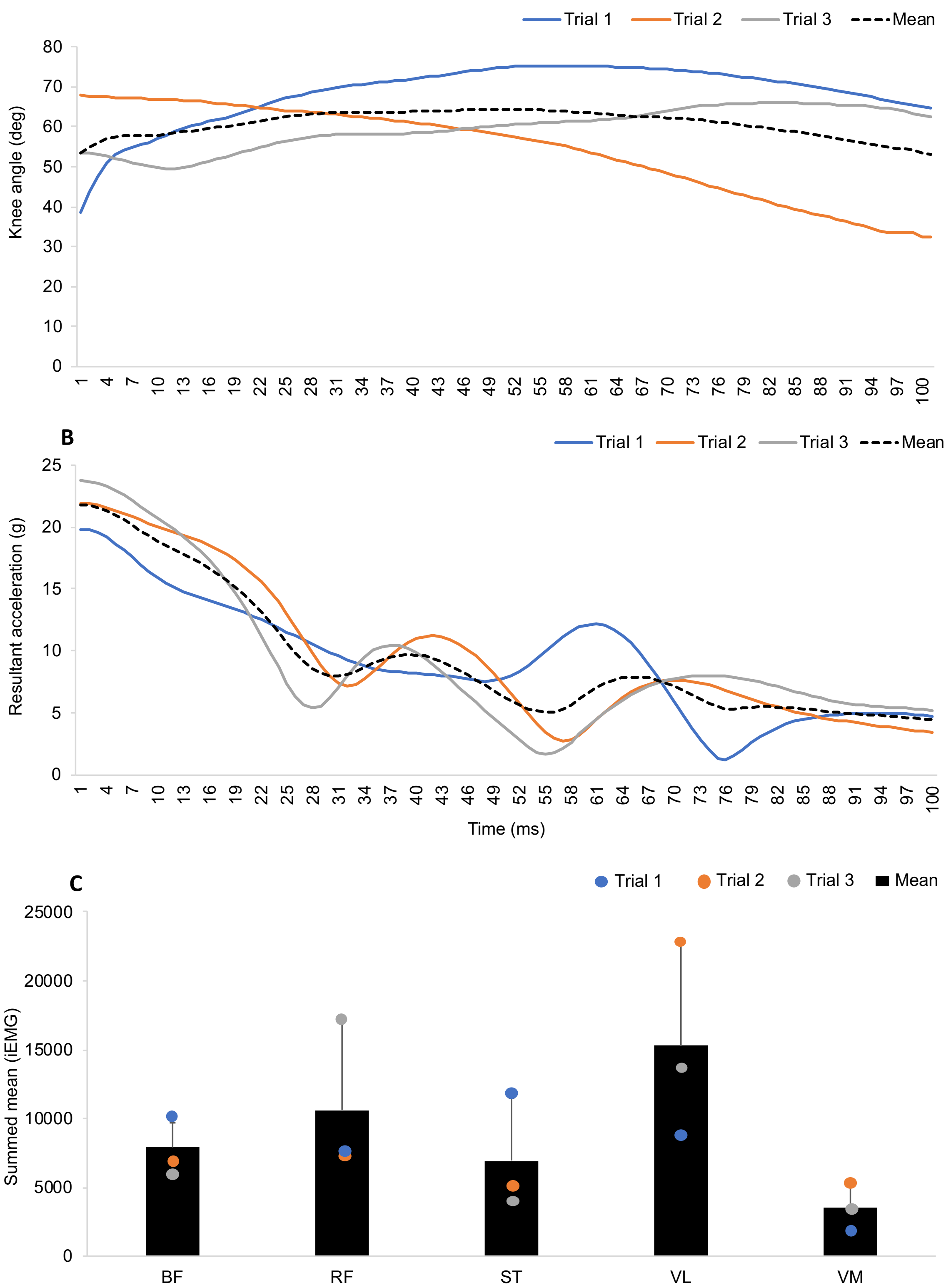

Figure 25. Data recorded post-IC (200 ms) phase of jump landing for subject 3 following 3 trials completed in the switch landing condition; part A = knee angle (deg), part B = resultant acceleration (g), part C = mean summed iEMG and peak EMG per trial.

Figure 27 presents data recorded by subject 4 during the 360 deg rotation post-IC phase (200 seconds) of landing. Part A shows peak knee angle recorded during 3 trials, with the highest peak knee angle at 111 deg attained in trial 2, and a mean knee angle of 100.4 deg across the 3 trials. Moreover, trial 2 produced the highest peak resultant acceleration at 24.4g, mean resultant acceleration was 24.0g after 3 trials (part B). Peak EMG recorded between trials was achieved by the RF (47892) and ST (24542) in trial 2, while peak EMG for the BF (28773) occurred in trial 1. Peak EMG for the VL (94792) and VM (65343) muscles was found in trial 3. Summed mean iEMG across all trials is also presented in part C.

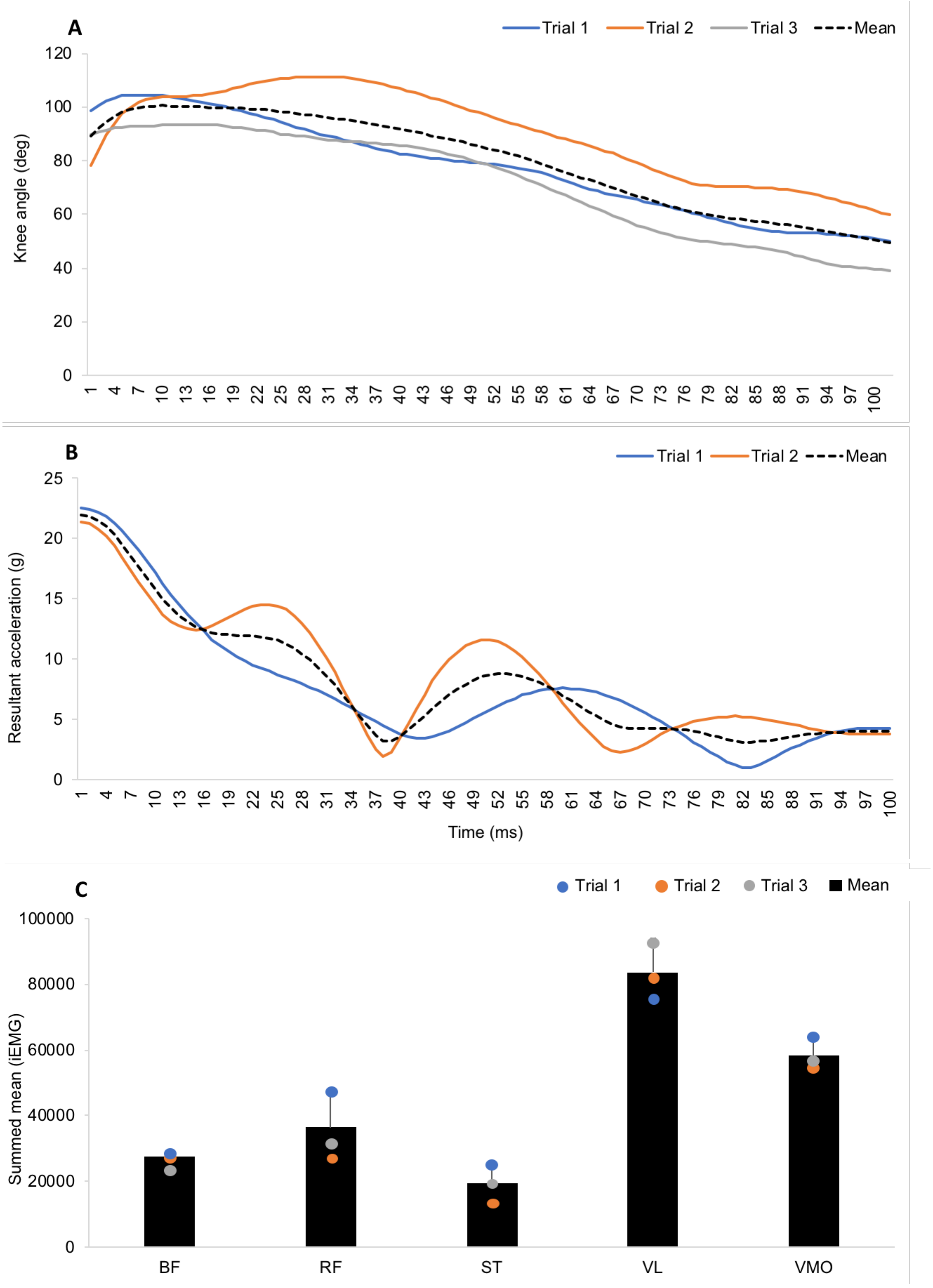

Figure 26. Data recorded post-IC (200 ms) phase of jump landing for subject 4 following 3 trials completed in the 360 deg rotation; part A = knee angle (deg), part B = resultant acceleration (g), part C = mean summed iEMG and peak EMG per trial.

Figure 28 includes data recorded by subject 5 during the post-IC phase (200 seconds) for the switch jump landing condition. The largest peak knee angle (part A) was recorded in trial 3 by the lead (left) leg at 74.1 deg, mean peak knee angle was

70.1 deg after three trials. The largest peak resultant acceleration (part B) was seen in trial 3 with 22.2g, mean acceleration for the three trials measured 19.8g. Peak muscle EMG recorded in trials showed RF (19802), ST (19802), VL (14208) and VM (10633) muscle groups all reported peak activity during trial 3, while peak BF (4704) activity was recorded in trial 2 (BF activity for trial 3 was not available for analysis) (part C). Summed mean iEMG across all trials is also presented in part C.

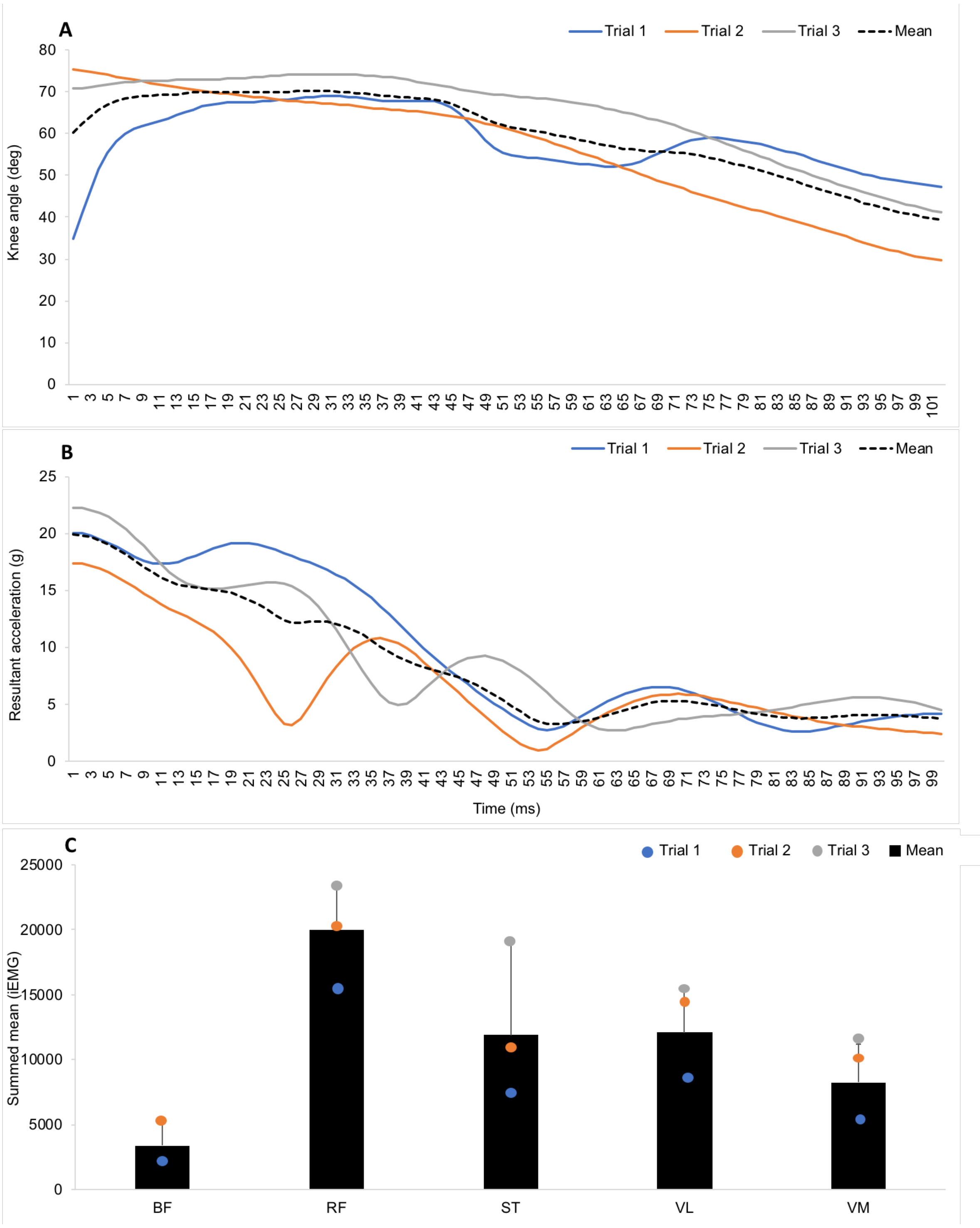

Figure 27. Data recorded post-IC (200 ms) phase of jump landing for subject 5 following 3 trials completed in the switch condition; part A = knee angle (deg), part B = resultant acceleration (g), part C = mean summed iEMG and peak EMG per trial.

4.6 Summary of results

While summed mean iEMG activity between subjects showed large individual variations, some trends can be seen in the iEMG values for individual muscle groups. For example, larger ST and BF muscle activation values were seen in 3 out of 5 subjects during the regular pre-IC phase of landing, compared to the switch jump landing condition. Furthermore, higher BF, VL and VM activity was seen during the pre-IC phase for 3 out of 5 subjects during the 360 deg rotation jump landing compared to the regular and switch jump landing conditions. Subjects activated RF to a greater extent than any other muscle group during the pre-IC phase of the switch landing compared to all other landing conditions.

During the post-IC phase, summed mean iEMG was higher in the ST muscle during the regular jump landing condition in 4 out of 5 subjects. The highest iEMG values were recorded by the VL muscle in both the switch and 360 deg rotation landing conditions by 4 out of 5 subjects. Mean iEMG in RF and VM muscle groups appeared to increase substantially in switch and 360 deg rotation post-IC landing conditions compared to the regular jump landing across subjects. In the hamstring muscle groups, the ST muscle exhibited large increases in mean peak activation during the post landing phase across all conditions. In contrast, mean iEMG values for the BF showed large fluctuations in activation across the three conditions, between subjects.

The highest mean EMG in the regular landing condition was recorded by subject 4, during trial 1 by the VM muscle 77426 post-IC. This was accompanied by a resultant acceleration of 20.52g, the lowest resultant value recorded across the 3 trials. VM summed mean iEMG 64809, SD± 12767 was also the highest value recorded across subjects in the regular landing condition. Trial 3 of 3 showed the highest recorded resultant acceleration at 23.53g, although this did not correspond to higher peak EMG values. Knee angle and knee angular velocity data were not available for trial 3.

In the switch landing condition, the highest mean peak EMG was recorded by the VM muscle at 92483 post-IC, by subject 4 in trial 2 of 2. With data available for just 2 trials by subject 4, VM activity was found higher than all other assessed muscle groups. Mean peak EMG for the VM also corresponded with a larger resultant acceleration of 19.54g. Peak knee angle of the left (lead) leg was 73.8 deg of knee flexion and peak knee angle of velocity was measured at 130.23 deg/s.

During the 360 deg rotation condition, the highest mean iEMG was seen by the VL muscle at 83725 post-IC, by subject 5. Trial 3 of 3 produced the highest mean peak EMG of 94792. VL activity was greater than all other EMG values recorded across the 5 muscle groups. Resultant acceleration recorded for trial 3 was 23.31g, which was slightly lower than the resultant acceleration found in trials 1 (24.40g) and 2 (24.33g) respectively. Peak knee angle of the left (lead) leg recorded post-IC in trial 3 was 93.63 deg of knee flexion. Peak knee angle of velocity data was not available for this trial.

Table 2. Trial summed mean EMG (iEMG) recorded for all 5 muscle groups in pre and post-IC phases, for the regular landing condition (n=5).

Regular - EMG Pre-IC					**Regular - EMG Post-IC**				
Subject 1	TRIAL 1	TRIAL 2	TRIAL 3	AV / SD		TRIAL 1	TRIAL 2	TRIAL 3	AV / SD
BF	6738.79	5942.71	5742.57	6141.36 ± 526.98	BF	18111.13	12410.11	15290.11	15270.44 ± 2850.56
RF	7808.21	10488.48	5956.86	8084.51 ± 2278.41	RF	7974.16	8542.96	3946.61	6821.24 ± 2505.70
ST	4429.86	6736.54	2504.43	4556.94 ± 2118.91	ST	5387.22	9422.26	4523.40	6444.29 ± 2614.91
VL	6105.33	5064.38	4807.77	5325.82 ± 687.15	VL	5958.07	8038.15	3889.48	5961.90 ± 2074.34
VM	2347.16	2805.86	1173.19	2108.73 ± 842.04	VM	3914.58	6728.77	2519.24	4387.53 ± 2144.24
Subject 2									
BF	3574.86	3155.31	0.00	2243.38 ± 1954.12	BF	4328.45	4178.88	0.00	2835.77 ± 2457.00
RF	23841.32	25490.24	0.00	16443.85 ± 14264.64	RF	34647.96	36702.09	0.00	23783.34 ± 20622.57
ST	15385.28	15510.86	0.00	10298.71 ± 8919.17	ST	50936.40	51303.50	0.00	34079.96 ± 29514.69
VL	13631.50	14032.11	0.00	9221.20 ± 7988.31	VL	21802.12	21993.00	0.00	14598.37 ± 12642.92
VM	13943.18	12601.35	0.00	8848.17 ± 7692.06	VM	25527.26	22807.50	0.00	16111.58 ± 14019.15
Subject 3									
BF	9517.45	14423.67	14423.67	12788.26 ± 2832.61	BF	10183.31	11292.35	17099.55	12858.40 ± 3714.57
RF	3647.24	7446.93	2926.51	4673.56 ± 2428.69	RF	6230.02	6942.37	6602.69	6591.69 ± 356.30
ST	12821.59	13627.00	20289.11	15579.23 ± 4098.70	ST	10628.73	20777.95	24880.48	18762.38 ± 7336.55
VL	3330.96	4267.63	2688.30	3428.96 ± 794.21	VL	11789.86	9200.60	13644.62	11545.02 ± 2232.10
VM	1000.21	1328.35	775.97	1034.84 ± 277.81	VM	2587.56	2307.64	3269.06	2721.41 ± 494.49
Subject 4									
BF	13892.24	12615.67	11235.72	12581.20 ± 1328.60	BF	19201.01	25650.56	20101.13	21650.90 ± 3492.92
RF	3716.36	2891.53	3037.75	3215.21 ± 440.12	RF	28500.05	31673.42	33719.63	31297.70 ± 2629.99
ST	22222.30	21473.86	19113.25	20936.46 ± 1622.69	ST	37774.52	26750.74	27250.36	30591.87 ± 6225.37
VL	5750.89	3652.26	2768.89	4057.34 ± 1531.72	VL	37790.25	35466.34	31822.31	35026.30 ± 3008.21
VM	9544.82	6964.39	7058.17	7855.79 ± 1463.49	VM	77426.38	65104.44	51896.98	64809.26 ± 12767.26

Table 2. Continued.

Subject 5									
BF	10400.06	14564.56	12563.34	12509.32 ± 2082.78	BF	30451.94	23321.93	19596.86	24456.91 ± 5515.83
RF	4512.76	4512.76	1772.93	3599.48 ± 1581.84	RF	12903.26	13319.52	8590.54	11604.43 ± 2618.40
ST	33488.44	21451.21	29432.39	28124.01 ± 6124.35	ST	42966.47	43121.26	36352.78	40813.50 ± 3863.87
VL	2274.87	1393.56	1762.88	1810.43 ± 442.57	VL	11370.78	14518.03	8994.46	11627.75 ± 2770.73
VM	6814.65	2792.66	5203.63	4936.98 ± 2024.21	VM	5025.65	10194.12	5282.04	6833.93 ± 2921.83

** = Data unavailable for trial

Table 3. Trial summed mean EMG (iEMG) recorded for all 5 muscle groups in pre and post-IC phases, for the switch landing condition (n=5).

Switch landing – EMG Pre-IC					**Switch landing - EMG Post-IC**				
Subject 1	TRIAL 1	TRIAL 2	TRIAL 3	AV / SD		TRIAL 1	TRIAL 2	TRIAL 3	AV / SD
BF	8594.28	4843.02	6241.06	6559.45 ± 1895.79	BF	7144.38	11596.59	12993.18	10578.05 ± 3054.54
RF	6717.11	16604.30	14123.78	12481.72 ± 5144.06	RF	15048.87	3699.73	3271.16	7339.91 ± 6679.58
ST	2412.05	1218.39	1087.29	1572.57 ± 729.95	ST	4099.96	3477.92	4134.46	3904.10 ± 369.50
VL	9255.13	6525.04	7282.27	7687.47 ± 1409.43	VL	25286.18	27102.27	29346.04	27244.83 ± 2033.68
VM	3678.77	1988.38	3156.71	2941.28 ± 865.54	VM	12640.79	13452.00	14177.25	13423.34 ± 768.63
Subject 2									
BF	7978.98	7775.05	7516.19	7756.74 ± 231.94	BF	12587.45	8820.48	9988.30	10465.41 ± 1928.28
RF	9231.97	12516.50	13178.22	11642.23 ± 2113.41	RF	27205.76	24121.93	28233.89	26520.52 ± 2139.91
ST	14931.25	9725.90	21864.41	15507.187 ± 6089.72	ST	33335.43	28137.18	32542.03	31338.21 ± 2800.41
VL	5880.81	7768.35	2156.28	5268.47 ± 2855.70	VL	9359.87	5931.90	9431.08	8240.95 ± 2000.01
VM	2591.38	4310.38	1506.85	2802.86 ± 1431.68	VM	7944.26	5270.12	12927.02	8713.79 ± 3886.02
Subject 3									
BF	2905.43	7866.90	2445.80	4406.04 ± 3005.99	BF	10000.77	7211.79	6646.71	7953.09 ± 1795.71
RF	7620.02	12024.47	8658.03	9434.17 ± 2303.52	RF	6733.29	6906.52	18212.53	10617.44 ± 6578.11
ST	1757.20	3818.85	792.53	2122.86 ± 1545.94	ST	12150.95	5002.82	3606.69	6920.15 ± 4583.47
VL	1757.73	11137.51	795.91	4563.71 ± 5713.35	VL	8688.43	23325.81	13824.76	15279.66 ± 7426.36
VM	756.22	2297.06	611.51	1221.59 ± 934.18	VM	1925.63	5004.22	3675.84	3535.23 ± 1544.11
Subject 4									
BF	5345.07	8511.01	**	6928.04 ± 2238.66	BF	24482.30	27432.53	**	25957.41 ± 2086.13
RF	6505.85	13330.90		9918.37 ± 4826.04	RF	48483.60	64547.43		56515.51 ± 11358.84
ST	2907.45	4512.35		3709.90 ± 1134.83	ST	41243.01	27610.93		34426.96 ± 9639.34
VL	9342.20	15052.76		12197.47 ± 4037.98	VL	42902.95	64958.40		53930.67 ± 15595.56
VM	12571.36	26269.34		19420.35 ± 9685.93	VM	61635.55	91483.98		76559.76 ± 21106.03

Table 3. Continued.

Subject 5									
BF	3801.36	2930.24	**	3365.80 ± 615.97	BF	2128.53	4704.49	**	3416.50 ± 1821.48
RF	5453.58	8342.61	7411.44	7069.21 ± 1474.61	RF	16456.04	20926.19	22692.15	20024.79 ± 3214.29
ST	9977.64	14873.34	27245.62	17365.53 ± 8899.67	ST	6413.03	9542.14	19802.56	11919.24 ± 7004.13
VL	893.79	1637.58	2145.74	1559.03 ± 629.66	VL	8432.97	13682.78	14208.51	12108.08 ± 3194.58
VM	891.12	2236.81	4047.76	2391.90 ± 1584.02	VM	4948.99	9276.70	10633.22	8286.30 ± 2986.71

** = Data unavailable for trial

Table 4. Trial summed mean EMG (iEMG) recorded for all 5 muscle groups in pre and post-IC phases, for the 360 deg rotation landing condition (n=4).

360 deg rotation landing - EMG Pre-IC					**360 deg rotation landing - EMG Post-IC**				
Subject 1	TRIAL 1	TRIAL 2	TRIAL 3	AV / SD		TRIAL 1	TRIAL 2	TRIAL 3	AV / SD
BF	15481.45	10349.24	8117.73	11316.14 ± 3775.88	BF	13007.54	14453.33	10974.63	12811.83 ± 1747.59
RF	7240.08	5051.82	5867.74	6053.21 ± 1105.86	RF	12369.19	17965.62	7276.82	12537.20 ± 5346.38
ST	6084.66	2133.87	3488.30	3902.27 ± 2007.67	ST	2197.86	2330.64	3954.25	2827.58 ± 977.97
VL	3288.37	3229.47	6440.30	4319.38 ± 1837.01	VL	16440.16	15094.62	15207.71	15580.83 ± 746.35
VM	2029.57	1927.09	3459.02	2471.89 ± 856.41	VM	12622.77	15196.35	17080.14	14966.41 ± 2237.56
Subject 2									
BF	**	**	**	**	BF	**	**	**	**
RF					RF				
ST					ST				
VL					VL				
VM					VM				
Subject 3									
BF	**	16276.06	10597.41	13436.73 ± 4015.41	BF	**	10272.39	10233.56	10252.97 ± 27.46
RF	4881.22	20174.28	23627.49	16227.66 ± 9976.85	RF	7587.69	33679.57	20067.37	20444.87 ± 13050.03
ST	41668.39	24809.63	4529.34	23669.12 ± 18595.77	ST	20799.17	8304.53	7151.00	12084.90 ± 7568.78
VL	19089.02	23244.78	7522.73	16618.84 ± 8146.90	VL	29602.71	28864.45	35342.86	31270.00 ± 3546.46
VM	4387.63	2828.45	2221.15	3145.74 ± 1117.55	VM	7088.61	7394.53	7698.12	7393.75 ± 304.76
Subject 4									
BF	16035.11	23819.17	11528.47	17127.57 ± 6217.75	BF	28773.08	28277.71	25707.73	27586.17 ± 1645.53
RF	9620.58	6351.62	4062.20	6678.13 ± 2793.54	RF	47892.30	28357.35	32790.36	36346.67 ± 10241.54
ST	8840.22	9243.24	4474.78	7519.41 ± 2644.42	ST	24542.49	14001.47	20318.14	19620.69 ± 5305.01
VL	17796.48	22125.25	11171.73	17031.15 ± 5516.72	VL	75079.96	81304.25	94792.36	83725.52 ± 10076.78
VM	17641.15	24938.19	17605.76	20061.69 ± 4223.20	VM	65343.19	54349.42	54845.53	58179.37 ± 6209.00

Table 4. Continued.

Subject 5									
BF	19212.65	7598.83	**	13405.74 ± 8212.21	BF	10438.32	13056.92	**	11747.61 ± 1851.63
RF	9481.83	9786.76		9634.29 ± 215.62	RF	40064.49	25341.03		32702.75 ± 10411.05
ST	11329.76	16812.81		14071.28 ± 3877.10	ST	37172.54	27822.93		32497.73 ± 6611.17
VL	4456.01	4926.38		4691.19 ± 332.61	VL	15354.77	12468.53		13911.64 ± 2040.88
VM	1454.14	3705.15		2579.64 ± 1591.71	VM	10352.73	6858.16		8605.44 ± 2471.04

** = Data unavailable for trial

Table 5. Trial peak % MVC and mean MVC % recorded for all 5 muscle groups in pre and post-IC phases, for the regular jump landing.

Regular jump landing - Pre-IC - Max % MVC					**Regular jump landing - Post-IC - Max % MVC**				
	TRIAL 1	TRIAL 2	TRIAL 3	Mean		TRIAL 1	TRIAL 2	TRIAL 3	Mean
Subject 1									
BF	97.14	67.00	78.90	81.01	BF	103.89	55.98	87.27	82.38
RF	22.42	23.71	14.11	20.08	RF	69.35	58.53	69.17	65.68
ST	32.90	56.73	26.32	38.65	ST	24.95	40.51	42.70	36.05
VL	46.10	26.86	39.19	37.38	VL	80.04	59.46	77.15	72.22
VM	19.63	20.07	11.94	17.21	VM	43.44	50.16	48.43	47.34
Subject 2									
BF	58.17	72.63	**	65.40	BF	163.41	69.72	**	116.56
RF	73.59	116.17		94.88	RF	151.59	153.82		152.70
ST	76.30	98.22		87.26	ST	112.99	189.98		151.48
VL	81.80	63.25		72.52	VL	134.25	141.30		137.78
VM	63.06	59.33		61.20	VM	116.54	111.78		114.16
Subject 3									
BF	102.21	101.76	121.33	108.43	BF	115.52	63.75	96.21	91.82
RF	21.56	18.75	17.07	19.13	RF	71.07	48.12	51.23	56.81
ST	110.05	145.34	128.99	128.12	ST	110.66	73.15	103.15	95.65
VL	51.25	36.79	60.36	49.47	VL	102.91	86.44	75.96	88.44
VM	27.50	25.94	51.04	34.83	VM	63.51	113.94	47.70	75.05
Subject 4									
BF	116.66	98.87	97.15	104.23	BF	89.53	188.10	71.33	116.32
RF	91.80	67.62	46.82	68.75	RF	124.08	115.31	121.49	120.29
ST	138.09	152.24	153.45	147.93	ST	125.50	116.06	110.77	117.44
VL	95.18	89.67	62.19	82.35	VL	92.44	85.53	128.39	102.12
VM	51.87	54.96	48.36	51.73	VM	68.81	71.63	106.36	82.27
Subject 5									
BF	56.42	51.67	45.19	51.09	BF	82.06	113.68	88.31	94.68
RF	33.24	35.47	15.88	28.19	RF	61.38	73.34	82.20	72.30
ST	64.18	62.27	55.09	60.51	ST	98.75	71.09	75.65	81.83
VL	28.37	28.75	20.39	25.84	VL	82.66	70.24	60.54	71.15
VM	32.54	26.20	20.77	26.50	VM	92.49	80.30	53.48	75.42

Table 6. Trial peak % MVC and mean MVC % recorded for all 5 muscle groups in pre and post-IC phases, for the switch jump landing.

Switch jump landing - Pre-IC - Max % MVC					**Switch jump landing - Post-IC - Max % MVC**				
	TRIAL 1	TRIAL 2	TRIAL 3	Mean		TRIAL 1	TRIAL 2	TRIAL 3	Mean
Subject 1									
BF	88.05	115.54	74.55	92.71	BF	92.17	91.32	65.83	83.11
RF	21.39	40.84	49.93	37.38	RF	63.05	49.74	52.18	54.99
ST	80.31	76.87	79.73	78.97	ST	32.95	33.18	21.42	29.18
VL	38.77	30.64	27.41	32.27	VL	76.97	87.98	65.93	76.96
VM	15.04	18.06	11.16	14.75	VM	69.18	43.90	55.79	56.29
Subject 2									
BF	36.36	30.99	41.49	36.28	BF	68.50	51.17	98.37	72.68
RF	59.39	57.26	42.55	53.06	RF	159.50	146.19	113.28	139.65
ST	75.86	85.65	75.70	79.07	ST	87.86	107.38	129.35	108.19
VL	74.50	100.38	70.73	81.87	VL	88.93	106.88	105.52	100.44
VM	47.74	82.58	37.36	55.90	VM	77.83	76.87	81.76	78.82
Subject 3									
BF	131.20	116.35	103.15	116.90	BF	115.19	95.30	84.74	98.41
RF	22.12	30.05	18.16	23.44	RF	59.72	72.09	68.77	66.86
ST	151.15	120.69	51.98	107.94	ST	62.78	100.64	100.61	88.01
VL	49.83	34.35	33.20	39.13	VL	85.69	94.39	89.76	89.95
VM	34.34	25.61	27.71	29.22	VM	140.81	78.59	75.32	98.24
Subject 4									
BF	124.14	57.60	98.10	93.28	BF	89.44	122.48	177.44	129.79
RF	32.81	36.76	27.53	32.37	RF	114.68	146.39	147.44	136.17
ST	193.71	117.84	155.05	155.53	ST	102.43	118.57	92.41	104.47
VL	45.02	86.24	65.33	65.53	VL	100.07	97.59	91.09	96.25
VM	52.31	54.07	48.83	51.74	VM	130.40	190.76	187.17	169.44
Subject 5									
BF	52.18	50.46	**	51.32	BF	103.36	121.27	**	112.32
RF	28.84	32.20		30.52	RF	137.56	172.15		154.85
ST	50.99	56.02		53.50	ST	185.96	133.18		159.57
VL	42.66	79.00		60.83	VL	113.22	184.08		148.65
VM	18.83	37.18		28.01	VM	103.23	117.15		110.19

Table 7. Trial peak % MVC and mean MVC % recorded for all 5 muscle groups in pre and post-IC phases, for the 360 deg rotation jump landing condition (n=4).

360 deg rotation jump landing - Pre-IC - Max % MVC					**360 deg rotation jump landing - Post-IC - Max % MVC**				
	TRIAL 1	TRIAL 2	TRIAL 3	Mean		TRIAL 1	TRIAL 2	TRIAL 3	Mean
Subject 1									
BF	110.65	95.56	66.72	90.98	BF	85.89	85.44	76.72	82.68
RF	20.97	11.30	18.12	16.79	RF	66.74	61.49	51.42	59.89
ST	107.54	59.28	58.84	75.22	ST	21.71	53.50	51.85	42.36
VL	32.21	16.72	34.09	27.67	VL	88.18	95.21	95.74	93.04
VM	12.91	3.77	32.59	16.43	VM	57.93	42.75	59.02	53.23
Subject 2									
BF	**	**	**	**	BF	**	**	**	**
RF					RF				
ST					ST				
VL					VL				
VM					VM				
Subject 3									
BF	139.90	113.07	98.70	117.22	BF	76.59	116.21	95.76	96.19
RF	27.43	47.33	51.16	41.97	RF	83.11	68.11	67.29	72.84
ST	168.55	99.12	179.03	148.90	ST	98.51	64.05	68.34	76.97
VL	54.08	51.43	74.69	60.07	VL	113.10	130.12	94.36	112.53
VM	39.32	23.85	16.06	26.41	VM	56.35	64.40	62.96	61.24
Subject 4									
BF	78.11	45.00	**	61.56	BF	118.13	119.84	**	118.99
RF	76.91	68.27		72.59	RF	100.79	120.16		110.47
ST	181.73	169.32		175.52	ST	125.76	134.27		130.02
VL	72.04	88.98		80.51	VL	67.54	87.72		77.63
VM	60.79	62.17		61.48	VM	68.94	124.67		96.80
Subject 5									
BF	114.12	100.30	57.48	90.64	BF	101.48	96.33	83.37	93.73
RF	43.66	26.91	32.28	34.28	RF	135.94	96.02	97.39	109.78
ST	41.72	28.97	21.49	30.73	ST	96.87	51.47	69.87	72.74
VL	109.86	141.81	197.81	149.82	VL	313.34	352.69	403.35	356.46
VM	30.37	31.62	33.26	31.75	VM	82.19	87.90	82.04	84.05

Table 8. Peak and mean resultant acceleration (g) recorded across regular, switch and 360 deg rotation jump landing conditions (n = 5).

	REGULAR (shown as g)				SWITCH (shown as g)				360 deg ROTATION (shown as g)			
	TRIAL 1	**TRIAL 2**	**TRIAL 3**	**AV / SD**	**TRIAL 1**	**TRIAL 2**	**TRIAL 3**	**AV / SD**	**TRIAL 1**	**TRIAL 2**	**TRIAL 3**	**AV / SD**
Subject 1	22.04	24.7	22.59	23.11 ± 1.40	21.37	13.26	17.55	17.39 ± 4.06	20.82	20.27	22.18	21.09 ± 0.98
Subject 2	24.93	19.65	**	22.29 ± 3.73	21.47	20.20	24.78	22.15 ± 2.36	**	**	**	**
Subject 3	26.92	26.63	15.25	22.93 ± 6.66	19.82	21.87	23.76	21.81 ± 1.97	16.34	21.24	24.85	20.81 ± 4.27
Subject 4	20.52	21.46	23.53	21.83 ± 1.54	17.12	19.54	**	18.33 ± 1.71	24.40	24.33	23.31	24.01 ± 0.61
Subject 5	17.91	20.04	21.42	19.79 ± 1.77	20.00	17.40	22.21	19.87 ± 2.41	22.49	21.39	**	21.94 ± 0.78

** = Data unavailable for trial.

5.1 Introduction

The main aim of the present study was to assess the biomechanical demands of regular, switch and 360 deg rotation snowboard landings in five elite freestyle snowboard athletes. And secondly identify differences between conditions and pre/post-IC landing phases. For the first time, results from this investigation will provide sport practitioners and coaches with an insight into the physical rigours facing elite freestyle athletes perform landings commonly seen in training and competition. This section will now provide a critical discussion of the key findings and rationale for the variance in results found between subjects and conditions.

Amongst the three conditions the largest peak impact force (acceleration) measured during the landing phase was found in the regular (21.99g) and 360 deg rotation (21.96g) conditions. The switch (19.91g) landing produced marginally less impact force by comparison. Peak knee angle in the regular condition recorded the least amount of knee flexion at IC (19 deg) in comparison to the switch (48 deg) and 360 deg rotation (82 deg) conditions. Yet, knee angle measured during the absorption phase of landing (post-IC) showed athletes performed greater overall mean knee flexion in the regular trials than in the switch and 360 deg rotation. Knee angular velocity indicated that the 360 deg rotation required the quickest and most rapid change in knee flexion angle (within <0.7ms) post-IC landing, which also links with high peak acceleration forces found. In contrast, knee angular velocity in the switch condition revealed knee flexion occurring over a longer time frame (<0.9ms) in comparison to 360 deg rotation condition, this also coincides with smaller acceleration forces found. Group summed mean integrated EMG (iEMG) revealed higher overall muscle activation post-IC versus pre-IC in the majority of muscles in all conditions, as hypothesised. Further, higher overall mean iEMG activity was recorded in the BF, RF, VL and VM muscles post-IC in 360 deg rotation, as hypothesised. Highest mean iEMG post-IC in the ST was found in the regular jump landing condition, which was unexpected.

Group mean activation patterns were observed in muscles between landing trials. For instance, higher mean iEMG ST activity was observed post-IC during regular landings, whereas higher overall quadricep (RF, VL, VM) activation was seen in switch and 360 deg rotation post-IC jump landings. In contrast, elevated hamstring (BF, ST) activation compared to quadriceps was found in the regular and 360 deg rotation trials pre-IC. Therefore, it could be implied that greater relative hamstring preactivation found in the rear stance leg during regular and 360 deg rotation landings was a preparatory mechanism for more severe landings found. Conversely, two out of the three quadricep (RF, VL) groups recorded superior values pre-IC in the switch landing condition in the lead snowboard leg. This also corresponded with higher mean RF, VL and VM iEMG activity post-IC in the switch landing. As well as, higher mean iEMG quadricep activity post-IC in the switch and 360 deg rotation trials. Another finding of this study was elevated muscle activity in the pre-IC phase corresponded with amplified muscle activity in the post-IC phase of landing. There was also a clear relationship between higher large peak acceleration forces on landing and greater muscle activation.

5.2 Snowboard acceleration in response to landing

Snowboard landing acceleration values ranging 13.26g to 26.92g are the first ever values reported during snowboard jump landings by an elite population, captured in a training session. The findings are similar to results published by Zhang et al. (2008) who reported 22.24g measured by the calcaneus during 30cm vertical drop landings. Also, a study conducted by Lundgren et al. (2016) observed elite surfers record up to 21.4g peak tibial accelerations during a jump-landing from a mini-trampoline onto a foam surfboard located on top of a soft-landing mat. Interestingly, authors matched peak tibial acceleration with peak vertical landing force during CMJ profiling and showed surfers sustained in excess of 6 times bodyweight during landings. Because higher peak accelerations were found in the current study in comparison to the values reported by Lundgren et al., (2016), it is proposed that subjects in the current study may have experienced forces in excess of 6 times body mass (relative) during snowboard landings. To substantiate this claim, future investigations assessing landings should incorporate force plate CMJ profiling to enable landing acceleration to be expressed relative to body mass. This is a common and helpful reference for physical preparation coaches to quantify sport demands when designing training programmes (Determan et al., 2010).

Interestingly, peak snowboard acceleration values obtained in the current study are in fact smaller than peak values noted in majority of vertical drop-landing studies with non-elite and athletic populations in the laboratory environment. It is well accepted landing height corresponds with greater peak acceleration cited in numerous papers (Zhang et al., 2008, Tran et al., 2010, Ali et al., 2014). Yet these studies reported data using significantly lower drop heights (30-90cm) and in many cases found significantly higher peak acceleration values compared with the current study. Moreover, the primary objective in the mentioned papers was to assess a vertical stuck landing with no horizontal velocity reported. Conversely, a sloped landing has been found to increase relative horizontal velocity at impact, resulting in less overall vertical impact (Turnbull et al., 2011, Hubbard and Swedberg, 2012). This may explain why reduced snowboard acceleration was seen in this study despite a larger landing height used against methods in the existing literature (Zhang et al., 2008, Tran et al., 2010, Lundgren et al., 2016). This consideration was also seen in skateboard ramp landings were mild relative impact loads of 4-5 were reported (Frederick et al., 2006). With this in mind, and in conjunction with findings recorded in the current study, it can be suggested that sloped landings increases snowboard horizontal acceleration, in comparison to vertical acceleration, which may be greater in flat landings.

One of the key findings from this study was the difference in landing acceleration found between conditions. It was hypothesised landings of greater technical difficulty (rotation) would sustain higher peak acceleration, although this was not the case. Mean acceleration data reported in the regular (21.99g) and 360 deg rotation (21.96g) conditions were almost identical. A possible explanation for this is a number of subjects ‘knuckled’ the landing on their initial landing attempts. In other words, athletes landed on the upper edge of the landing ramp creating a large impact moment between the snowboard and landing slope, resulting in higher mean acceleration data reported. Feedback from Park and Pipe snowboard coaches indicate that knuckling a landing versus a more efficient landing is more physical severe by comparison. Additionally, the large knee flexion values recorded in the regular landing condition revealed subjects may have accommodated for suboptimal landings by increasing overall knee flexion and work done by the legs. Similar impact reduction strategies are noted by other studies of which point out the influence of lower-limb kinematics as a method to attenuate landing impact force (Zhang et al., 2008, Zhang et al., 2000). While unexpected, this finding demonstrates the increased severity involved during knuckled landings.

5.3 Limb kinematics in response to landing

Varying relationships were observed between knee joint angle and peak landing acceleration in this study. As hypothesised, subjects recorded increased knee joint flexion angle at the point of IC during switch and 360 deg rotation versus the regular landing condition. A reason for the increased knee joint flexion in the switch and 360 deg rotation trials could be explained by the feedforward mechanism, were the neuromuscular system was prepared for a more complex landing task. This is consistent with many drop-landing studies were anticipatory movements were found to achieve a more preferential landing outcome (Walsh et al., 2012, Bai and Fukumoto, 2013). Further, the rapid increase in knee joint angle in the regular landing trial represents the bodies response to impact loading, were increased knee joint flexion was used to provide shock absorption against acceleration force on landing (Yeow et al., 2009). This finding is consistent with numerous other studies were increased knee joint flexion may assist in protecting the knee from valgus collapse during landing (Shultz and Schmitz, 2009). Of particular, concern is the combination of reduced knee flexion, combined with a hip adduction (internal) moment, which may increase stress on the knee structures, specifically the ACL (Norcross et al., 2010, Hewett et al., 2005). A decreased knee angle has been associated with increased risk to knee injuries at the time of initial contact (Bates et al., 2013). Probably due to decreased lower-limb stiffness and greater GRF occurring throughout the landing phase (Tillman et al., 2004). Together reduced knee flexion angle and increased rotary forces may augment quadricep activation (Walsh et al., 2012) and increase knee injury risk. It would appear then, increased flexion range at the knee is a useful mechanism for snowboarders to accommodate and dissipate higher ground reaction forces on landing. Which may also mitigate joint tissue loading and reduce knee injury risk.

Interestingly, peak knee angle recorded in the three jump landing conditions did not follow an inverse-relationship with peak snowboard acceleration on landing. Despite the highest peak acceleration impact recorded in regular landing condition (21.99g), the lowest peak knee angle was seen on average in the regular landing trials (63 deg) at IC. Nonetheless, it would appear that high knee flexion angles are indicative of large landing impacts. For example, the largest peak knee angle was recorded in the 360 deg condition with 88d of knee flexion, with a peak snowboard acceleration of 21.96g. Similar findings are reported by other studies examining the relationship between acceleration and knee joint range on landing (Zhang et al., 2000, Zhang et al., 2008, Aizawa et al., 2016, DeVita and Skelly, 1992). It has been suggested peak knee angle at IC offers limited protection against impact, exposing limbs to greater shock (Lafortune et al., 1996). Were an increasing range of motion in lower extremity joints enables musculature to attenuate landing impacts during the shock reduction process (Zhang et al., 2000, Cortes et al., 2012).

Large peak acceleration impacts and rate of loading are key considerations to assess overall loading demands of landings. Knee angular velocity data presented in the current study showed all conditions imposed a high rate of loading to the body during landing. More specifically, angular velocity in the 360 deg rotation revealed subjects a rapid change in knee flexion during the first 7ms post-IC. This corresponds with higher peak acceleration forces recorded in the 360 deg condition. In contrast, angular velocity in the switch landing was comparatively higher than the 360 deg rotation at the point of IC, but over a longer time frame (9ms). This finding alone points out that knee angular velocity at the instant of landing does not predict a passive change in knee angle/angular velocity in the initial moments of landing. Nor does angular velocity predict peak acceleration landing force (Yu et al., 2006). Nonetheless, the variance in knee angular velocity data between conditions points out the abrupt nature of landing seen in the 360 deg rotation landing. Knee angular velocity data could not be reported for the regular landing condition.

5.4 EMG activity pre and post-IC

On average higher summed mean iEMG values were found post-IC versus pre-IC landing phase across conditions (see figures 7, 8 and 9). With exception, higher pre-

IC summed mean iEMG values were found in the ST and VL muscles for the regular and switch jump landing conditions only (figures 7 and 8). This finding is in line with the published literature assessing muscle activity pre/post drop-landings (Bai et al., 2011), but not in studies assessing jump-landings were EMG activity was reportedly higher in jump propulsion moments (Virmavirta and Komi, 1991). Furthermore, higher summed mean iEMG and peak % MVC were found in the majority of assessed muscles (BF, RF, VL, VM) in the 360 deg rotation jump landing. This is in agreement with the projected hypothesis, although higher iEMG values were found in the regular jump landing which was unexpected. There are several possible reasons for this finding. Firstly, this was the first-time subjects were exposed to this specific task, as mentioned previously subjects miscalculated distance to the landing slope from the drop and knuckled their first couple of landings, which produced a very large peak acceleration moment. Secondly, as subjects proceeded to complete repeat drop-landings its possible subjects altered their landing strategy to accommodate for the large impact landing force based on greater experiential learning about the task. In this instance, impact moderating behaviour provides an understanding for improved technique and motor behaviour following an experience of an abrupt landing task (Dyhre-Poulsen et al., 1991) which could have influenced EMG activity. Thirdly, large peak acceleration forces, combined with a small IC knee flexion angle, later increasing rapidly in response to landing impact, and greater EMG activity corresponds with findings also reported in the literature (Chappell et al., 2007, Zhang et al., 2008, Smith et al., 2009). The fact that a lower sum of mean iEMG was found in regular and switch conditions in comparison with the 360 deg rotation post-IC complies with the findings of other studies in the area. Greater initial knee flexion found at IC and greater quadricep (RF, VM, VL) activation was found to attenuate landing impact force (Zhang et al., 2000, Zhang et al., 2008).

Reviewing individual muscle activity pre and post-IC offers a different perspective to the sum of iEMG, presented. It would appear that higher pre-activation of quadriceps (RF, VM, VL), combined with greater knee flexion angle at IC (see figure 5) in the switch and 360 deg rotation trials may have resulted in lower peak acceleration forces. These findings align with recommendations in the literature. Using a large range of joint flexion in multiple structures combined with high levels of muscle MVC applied rapidly resulting in effective joint stiffness, and a change in the impulse-momentum relationship (Turnbull et al., 2011). In the current study, higher levels of muscle preactivation pre-IC demonstrates subjects increased muscle force to constrain large impact forces on landing. The tenants of lower-limb strength and rate of force development capacities are essential to enable the body to tolerate high GRF during landings in short loading times (McNitt-Gray et al., 2001, Determan et al., 2010, Secomb et al., 2016). In the switch and 360 deg rotation jump landing trials subjects performed less overall knee flexion post-IC, versus the regular landing, and demonstrated larger changes in knee angular velocity. Which indicates subjects achieved greater overall knee stiffness in switch and 360 deg rotation versus regular landings via greater neuromuscular activation (Turnbull et al., 2011, Horita et al., 2002).

Higher iEMG medial (ST) and lateral (BF) hamstrings pre activity was seen in the regular and 360 deg rotation trials, in comparison to activity in the switch landing conditions. The concept of muscle preactivation prior to the instant of landing has been largely explained by the feedforward mechanism (Dyhre-Poulsen et al., 1991, McNitt-Gray et al., 2001, Shultz et al., 2015). Numerous studies have documented elevated muscle activity prior to landing as an anticipatory mechanism to prepare the body for landing (Chappell et al., 2007, Bai and Fukumoto, 2013, De Britto et al., 2014). The source of this process is largely associated with visual sensory information providing the brain with feedback relating to external and internal environmental conditions. There are instances in which proprioceptive input is quicker than visual to enable a change in motor control, such as, in response to landing on an unstable surface (Prieske et al., 2013). Although, when this information is limited, it has been shown that an increase in hamstring activity during landing tasks occurs before joint loading in a feedforward control manner (Riemann and Lephart, 2002). This may lend some explanation for the elevated hamstring activity seen in the 360 deg rotation condition.

In the current study, increased hamstring (ST, BF) preactivation over quadriceps during rotational landings was found, which is similar to the findings in other studies (Bai et al., 2011, Pantoja et al., 2014, Bai and Fukumoto, 2013). And also, greater lateral hamstring preactivation was seen during more complex rotational jump-landing tasks in the current study (Pantoja et al., 2014). This finding also coincides with the study hypothesis of greater hamstring preactivation seen in rotational landings. Studies have also found increased lateral hamstring preactivation protects against knee adduction (valgus) moments, and reduced knee rotational torque stress (Bai and Fukumoto, 2013, Pantoja et al., 2014). Further, elevated coactivation of medial and lateral hamstring muscles during regular and 360 deg rotation conditions pre-landing, is similar to findings elsewhere in the literature (Bai and Fukumoto, 2013). It is possible that the coactivation of medial and lateral hamstrings reduces knee rotational stress, which is advantageous based on greater knee and ACL loading associated with knee valgus postures (Norcross et al., 2010, Davies et al., 2009, Determan et al., 2010).

The group mean responses post-IC across the three conditions indicate that. in the switch and 360 deg rotation landing trails, quadricep (RF, VL, VM) mean iEMG was higher than hamstrings, which corresponds with the kinematic and kinetic elements present on landing also reported in the current study. Interestingly, mean iEMG post-IC in the regular condition revealed elevated quadricep (RF, VM) and medial (ST) hamstring activation. This finding is consistent with quadricep and hamstring EMG activity recorded in drop-landings performed in the sagittal plane by Malfait et al. (2016). Moreover, increased medial hamstring and quadricep activity was consistent with low knee flexion angles on IC (<15 deg), which is similar to the group knee flexion angle (19 deg) at IC found in this study. Reduced knee flexion angles in conjunction with higher medial hamstring activation is acknowledged as an effective mechanism to reduce anterior tibia loading, and in turn counteract the load/strain acting on the ACL (Malfait et al., 2016). What’s more, increased medial hamstring activation pre and post-IC suggests subjects used a feedforward strategy to control the high peak acceleration forces and anterior tibial forces possibly induced by the VM activity on landing. In any case, increased hamstring activity concomitant with quadricep activation indicates increased mechanical work being done by the knee extensors and flexors to meet the high impact force demand imposed on landing (Blackburn et al., 2013).

Mean iEMG findings post-IC in switch and 360 deg rotation demonstrate a quadricep dominant strategy toward landings, as per the group average response. Figures 24 and 27 show results from two different subjects who completed the 360 deg rotation trials. Both subjects landed with high average knee flexion (68 deg and 90 deg) and experienced similar acceleration force at IC (21g and 22.5g) but produced very different peak EMG % activation patterns. Results of three different subjects following the switch landing trials again show distinctive mean iEMG activity indicating large a variance in muscle responses relative to landing conditions. In view of this, it is highly likely athletes possess different landing techniques acquired from personal experience which influenced the difference seen in knee angle at IC and corresponding muscle responses to impact loading. Moreover, differences in iEMG activity indicates muscle activation techniques are inherent to each subject's landing strategy. Neuromuscular and kinematic considerations have been discussed and compared with other investigations which recognise useful strategies for safe and effective landings. Like the feedback feedforward mechanism and quadricep and hamstring coactivation which prepare the body for severe landings and in turn, may reduce the risk of knee injuries in sport performance.

The discussion around muscle activity highlights clear differences between regular, switch and 360 deg rotation conditions, it should be reiterated that only one leg was fitted with EMG electrodes during the assessed jump landing trials. Therefore, readings obtained during switch landings in fact refer to activity of the lead snowboarding leg, while regular and 360 deg rotation landings denotes activity of the rear leg only. With this in mind, and in view of the reported findings, it could be implied manoeuvres performed in regular snowboard stance augments hamstring pre-activity of the rear snowboard leg, while switch landings produce greater quadricep preactivation in the lead snowboard leg. Strength asymmetries in elite snowboarders have been reported previously (Vernillo et al., 2015) which supports the notion that asymmetrical muscle activation patterns commonly occur in the sport. This is also supported by anecdotal reports from snowboarders who indicate the rear leg plays a more dominant role in jump take-off and landings. It's clear based on the findings that a difference in muscle behaviour exists between lead and rear legs in snowboard landings and landing tasks.

5.5 Recommendations for future work

The basis of this investigation was to increase understanding of critical jump landing movements that determine performance in freestyle snowsport. The investigation therefore is of great applied importance to the GB national Olympic team, coaches and athletes. While the study design and sensitivity of findings could be improved, the data collected in this study represents current challenges facing scientists working with elite snowboard teams and athletes. What this investigation may lack in scientific rigour, it provides the sport, coaches and athletes with invaluable information currently lacking in the sport which can be used to support knowledge and applied practice.

A small cohort of elite riders were assessed in this investigation, increasing the total number of athletes involved would likely increase the strength of the data. Findings from a larger subject number may offer a better insight into athletic capabilities that reflect a stronger impression of jump landing demands in elite SS and HP riders. While the subject group in the current studies were small in number, the total number of subjects evaluated were at the time elite athletes representing Team GB at World Cup and Olympic competitions. Therefore, the number of subjects available is currently limited by total number of elite athletes which represent the Great Britain Park and Pipe team for elite slopestyle snowsport.

Data collection from a single training session included several design issues in the main investigation which only became apparent during testing. Repeated data collection would have ensured data collection of kinematic data were resolved. For example, motion capture cameras had to be readjusted part-way through the recording of regular jump landing trails, which explains poor data availability pre and post-IC across conditions. Secondly, ankle kinematic data had to be discounted from final analysis due to issues with light markers falling off the athlete’s ankles, bindings and snowboard upon landing impact. A number of these issues could have been addressed with further pilot testing and solutions found to improve light marker contact with the body and equipment. Furthermore, because the indoor snowdome was occupied for public use throughout daylight hours this meant limited opportunity to perform reliability testing of the methods. Future investigations should also strongly consider the type of jump landing examined. The drop platform used in the current study allowed the landing phase to be isolated, providing discrete analysis of jump landing data. This insight was an important first step in undiscovered territory, bridging scientific analysis of performance actions done in the sport. Future assessments should look to incorporate analysis of a complete jump take-off and landing, providing a complete profile of a jump landing.

The kinematic results obtained in this study showed that elite freestyle snowboard athletes performed jump landing tasks with a specific movement strategy occurring at the knee joint. The differences shown between each landing task suggests that a greater amount of knee flexion, and therefore effort to absorb landing impact occurs in rotational jump landing manoeuvres. With this considered, and from the obvious differences found between subjects in response to snowboard jump landings, the question still remains – is there an ideal or optimal technical model for sloped snowboard jump landings? As discussed, the differences found during knuckled and non-knuckled snowboard landings indicates that landing on the sweet-spot (the area between the knuckle and flat) of a jump imposes significantly less landing impact (shock), and therefore is preferential. Moreover, an observation of riders during data collection showed that riders contacted the landing slope with the rear of the snowboard first, followed by the middle and front of the board in sequence order. It's worth noting, that there are instances in the sport were the entire surface area of the snowboard will contact the ground/slope at the same time. But this tends to occur during non-sloped landings, such as, exiting from a flat rail. Encouraging contact with the slope using a rear to front board sequence enables the rider to sustain forward horizontal momentum of the snowboard and utilise the boards reflexive engineering to absorb and control landing impact along with use of the body's limbs.

As discussed, the kinematic behaviour of lower and upper limb structures plays a critical role in performing successful, controlled jump landing actions. Ideally, riders must possess sufficient active and passive joint mobility, and also a capacity for rapid joint loading to decelerate lower and upper limbs in synergy during landings. An ideal model for limb kinematics in snowboard landings would occur as follows: Upon initial impact with the snow, the lower-body must begin to actively transition from an extended to flexed lower-limb postures to counteract GRF acting on the body via the snowboard. While the lower-limbs undergo large, and rapid joint flexion, the upper-limbs, and more specifically the trunk begin to flex and rotate toward the nose of the snowboard to aid the lower-limb structures and dissipate GRF loading throughout the kinetic chain. The lower and upper limbs continue work passively, and in unison, until the rider has created enough downward pressure into the snowboard, and the change in limb position has arrived at a controlled stop.

Critically, riders must possess the ability to control three-dimensional joint impact loading at high loading speeds. This includes the rider's ability to control rapid, high knee joint flexion angles, and excessive knee valgus postures of the rear leg to achieve balance across the centre of mass, limb stiffness and board control. Whilst unfavourable, developing athlete’s ability to control these postures, initially under slow, purposeful loading rates would be advisable in preparation for rapid joint loading imposed by sloped jump landings. Physical preparation coaches should aim to develop rider’s passive knee joint control in positions which mimic loading requirements and positions of snowboarding. And also remain cognisant of the importance of developing dynamic knee joint control to reduce the risk of sport related knee injuries.

In an attempt to assess movement characteristics of the knee joint during sloped snowboard jump landings, this study has discussed the findings of knee joint angle and knee angular-velocity measures. While the results provided some insight into knee joint flexion in response to rapid impact loading, the measures fail to provide an understanding of the rate of multiplanar loading acting at the knee during landings. With a large proportion of snowboard injury research discussing the prevalence of ACL injury linked to knee valgus postures, future investigations should look to incorporate a more specific assessment measure to examine three-dimensional joint loading of the knee. With this in mind, the assessment of multi-planar acceleration of the knee joint could be incorporated into future investigations with the use of advanced IMS technology. This would serve as a better indication of knee joint loading in all three planes of motion and therefore provide a greater understanding of the knee injury mechanism risk to snowboarders. This level of analysis should be incorporated into future biomechanical studies.

In effort to describe the impact loading demands of regular, switch and 360d snowboard landing tasks, a tri-axial accelerometer was affixed to the center of the snowboard. The device successfully provided a measure of the snowboard’s peak acceleration, demonstrating the magnitude of impact during snowboard landings. This finding helps coaches and practitioners understand the rate of loading a snowboarder may experience during landings, and the relative acceleration imposed. In practice, this insight may assist coaches to understand the relative intensity of specific landing tasks, which would enable coaches to direct athletes to certain jumps and tricks to condition and prepare a rider to a level of landing intensity.

From a perspective of grading the physical demand of landing tasks, future investigations may wish to consider additional kinetic measures such as, peak force and time to stabilisation landing measures. With lightweight snowboard mounted force platforms situated underneath each binding, these measures would provide an understanding of the landing force imposed on the lower-limbs and effort required to decelerate impact landing force. In addition, time to stabilisation would also enable practitioners to assess the rate of braking force required by front and rear legs, and also the performance capability of athletes during landing manoeuvres. Again, this information would provide a stronger set of key performance indicators for the investigated tasks and identify specific performance demands of snowboard jump landings. It is recommended that these measures are investigated in future studies to build upon the work performed in this thesis.

CHAPTER 6. CONCLUSION

Results from this investigation represent novel information pertaining to the biomechanical demands in snowboard jump landings in elite freestyle snowboard athletes. Efforts were made to identify and evaluate key biomechanical demands, with analysis describing pre and post jump landing activity, and differences found between types of landing done in the sport. Because the methods examined have provided a likeness to the real-world sport actions, this information is of great applied significance to physical preparation coaches, technical coaches and scientists working with elite athletes in freestyle snowsport. Information gained from this research can be used to inform the prescription of injury prevention and athletic preparation programmes and provide coaches with a deeper understanding of the muscular and mechanical outcomes from snowboard jump landings.

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