The effects of differing sensory stimuli on landing mechanics during dual-tasking scenarios.

Luke David Scott

Student ID: 36175255

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Supervisors: Dr Bob Lauder and Dr Theo Bampouras

Abstract

Introduction: Non-contact Anterior Cruciate Ligament (ACL) injuries are an increasingly common injury within sports. However, research into how cognitive-motor dual-tasking, the act of simultaneously performing a cognitive and a motor task, affects landing mechanics is still in its relative infancy. Therefore, this study aims to investigate how presenting the cognitive stimuli via different sensory methods, including auditory which to this point has not been included in any previous dual-task research, affects common landing injury risk predictors during a vertical drop landing.

Methods: 30 participants (20 male, 10 female) performed a sports-simulating chest pass with a ball, similar to what would be seen in Netball or Basketball, following a vertical drop landing (VDL) from a 45cm box. The passing direction was given to participants mid-air via four different methods: a control, a visual stimulus, an auditory stimulus, and a simultaneous visual & auditory stimulus. Two-dimensional kinematics and kinetics were measured during 8 successful trials in each of the four conditions with the use of two cameras and dual-force platforms. The practical effects of differing stimuli on sporting performance were also assessed through the measurement of participants' total time to pass (TTP).

Results: Significant differences were shown between the control condition and the simultaneous visual & auditory stimulus, with decreases in peak ground reaction force (2.50 ± 0.526 vs 2.32 ± 0.558) relative to the participant’s body weight and increases in peak knee valgus angle (8.51 ± 14.0° vs 12.5 ± 16.0°) in participants’ right leg. Significant decreases were also found between auditory stimuli and all other conditions in participant's TTP.

Conclusion: The presence of a combination of visual and auditory stimuli altered the performance during both the cognitive and motor tasks. The presentation of Light & Sound simultaneously as a stimulus altered participants' landings with a decrease in force and an increase in peak knee valgus angle which are associated with a safer landing technique and potentially reduce injury risk. These findings may have implications for both the prediction and rehabilitation of lower limb injuries when including dual-tasking as a training method.

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Abbreviations

ACL – Anterior Cruciate Ligament

KVA – Knee Valgus Angle

pGRF – peak Ground Reaction Force

vGRF – vertical Ground Reaction Force

xBW – times body weight

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1. Introduction & Literature Overview

1.1 Introduction to ACL Injuries

Injuries sustained within sports not only impact athletes' health but also impose significant financial burdens on public health services and professional organizations. Eliakim et al. (2020) estimated that an average English Premier League team incurs losses of approximately £45 million per season due to injuries. On a broader scale, the Australian Institute of Health and Welfare (2023) reported that over £630 million was spent in Australia between 2018-19 on treating injuries caused by physical activities. These figures highlight the substantial economic impact of sports-related injuries. Analysing medically attended injuries in the United States from 2011 to 2014, Sheu and Hedegaard (2016) found that, of the 8.6 million injuries annually, 42% were to the lower extremities. This is consistent with an earlier study by Conn, Annest, and Gilchrist (2003), which identified that 53% of lower extremity injuries were tendon sprains or muscle strains. Moreover, falls were the leading cause of these injuries, underlining the need for preventive measures in sports and physical activities. Focusing on lower extremity injuries, knee injuries are one of the most common. In a study encompassing one hundred United States high schools, Fernandez, Yard, and Comstock (2007) observed that knee injuries accounted for 25% of all lower extremity injuries. Furthermore, these injuries were often severe, with knee injuries being the most common location requiring surgical repair. 67% of girls' total surgeries were due to knee ligament tears compared to 35% of total surgeries for boys. In the context of specific sports, knee injuries are a major concern, especially within team-based sports. For instance, Westermann et al. (2016) noted that in American Football, over a third of all lower extremity injuries among NCAA players were knee injuries, with 23% occurring in non-contact scenarios. This is particularly notable given the relatively low amount of non-contact time in American

Football. Similarly, in Basketball, knee joint injuries constitute an estimated 17.8% of total body injuries, as reported by Andreoli et al. (2018).

These findings highlight the prevalence of knee joint injuries within various sports, and we may see rates continue to rise as current trends indicate. One of the most devastating injuries an athlete can suffer is to the Anterior Cruciate Ligament (ACL), which is responsible for preventing anterior translation of the tibia at the knee joint as well as preventing excessive rotation of the tibia. The average return to sport duration for high-performance athletes suffering an ACL injury was a full calendar year, with youth athletes taking the longest to recover at a median return to sport time of almost 500 days (Rigg et al., 2023). Outcomes of ACL injuries can be even more destructive in recreational athletes. Over 60% of recreational athletes who underwent ACL reconstruction surgery didn't return to their sport, despite those who did return experiencing greater knee function, which was determined using the International Knee Documentation Committee evaluation form scores, a highly reliable method for assessing a person's symptoms and function following a knee injury or surgery (Grevnerts, Terwee and Kvist, 2015). Returning to sport was also associated with increased positive psychological outcomes, with those who returned to the same level of sport or higher reporting less depressive symptoms compared to those who did not return to sport (Filbay et al., 2016). The main reasons given for not returning were "not trusting the knee", "fear of new injury" and "poor knee function" (Ardern et al., 2014). Cruciate injuries not only lead to long rehabilitation processes for athletes to return to both daily function and their sports but also lead to nearly 7 times the likelihood of developing knee osteoarthritis later in life (Webster and Hewett, 2021).

A 2022 study published in The Lancet analysing the trends of knee injuries over the last 20 years in Australia showed that ACL injuries experienced the highest year-on-year increase of any form of knee injury, with adolescent female athletes experiencing an annual growth rate of over 10% (Maniar et al., 2022). This was in conjunction with data from between 2005 and 2015 from Victoria, Australia showing that ACL injuries in adolescents increased 148% over the 10-year period, with over half of all female ACL injuries occurring during team ball sports (Shaw & Finch et al., 2017). The sports responsible for the highest rates of ACL injuries in NCAA sports were Lacrosse and basketball, with a statistically significant increase in ACL injuries per year for Women’s basketball and soccer (Agel, Rockwood and Klossner, 2016). Women also experienced a greater injury rate per exposure than their male counterparts in all team ball sports recorded, with 60% of injuries occurring in non-contact situations versus only 40% of male ACL injuries.

1.2 ACL Structure

The ACL is a band-like structure made up of a pair of two dense bundles of collagen fibres. The ACL originates at the medial wall of the lateral femoral condyle and inserts into the middle of the intercondylar area (Figure 1.2, *Johns Hopkins Medicine, 2020)*). The ligament is typically between 22-41mm in length and 7-12mm in width. It crosses in an “X” like manner with the posterior cruciate ligament which provides the opposing resistance force to the ACL.

The ACL is responsible for producing approximately 85% of the restraining force during anterior tibial translation, which is the forward motion of the tibia (shin bone) relative to the femur (thigh bone). This is in addition to providing the knee joint with rotational stability by controlling internal tibial rotation which is the amount of rotation of the tibia relative to the femur (Domnick, Raschke and Herbort, 2016; Duthon et al., 2005; Dienst, Burks and Greis, 2002).

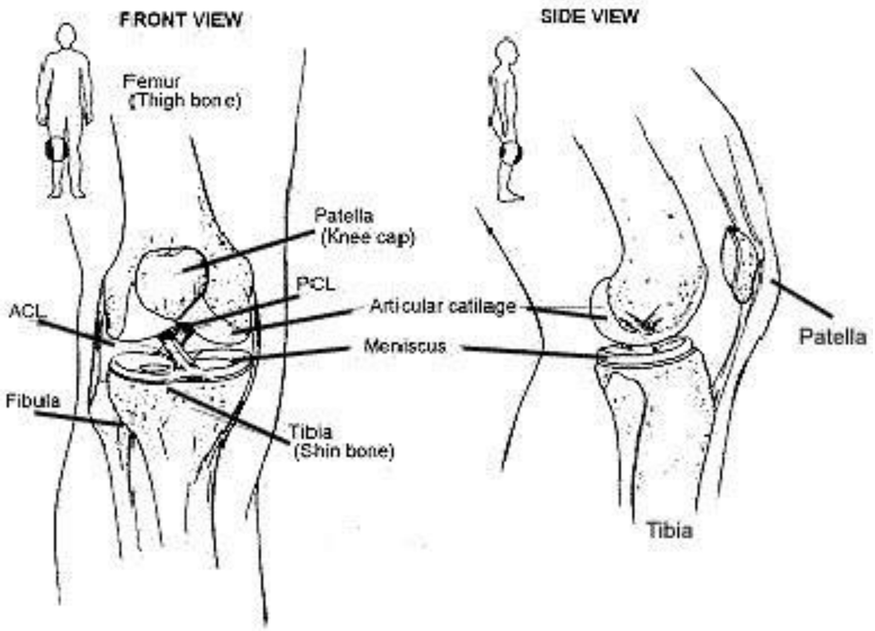


Figure 1.2*: Frontal and sagittal knee joint knee structure (Johns Hopkins Medicine, 2020).*

1.3 ACL Injury Mechanics

It is reported that between 60% and 95% of ACL injuries occur in non-contact situations with the majority occurring when an athlete must turn, decelerate, or land and when the vertical ground reaction force is five times the athlete's mass (Boden et al., 2000; McNair et al., 1999; Myklebust et al., 1998).

In a study of over 1700 athletes who sustained ACL injuries, almost half occurred during competition with non-contact injuries being the most common situation. The most common alignment of the knees at the time of injury was dynamic knee valgus, which occurs when the knees collapse inwards from the hip and ankle joints, accounting for half of all ACL injuries (Kobayashi et al., 2010). This abnormal movement pattern is referred to as dynamic due to the motion occurring throughout the motion of landing, during which medial knee displacement is observed and the knee will travel towards the body's centre line, crossing beyond the foot-thigh line throughout the motion (Wilczyński, Zorena and Ślęzak, 2020;.Schmidt, Harris-Hayes and Salsich, 2019). An analysis by Walden et al. (2015) of 39 ACL injuries in professional football players determined that 85% of the ACL injuries occurred during non-contact situations. The main mechanism for ACL injuries which was seen in almost half of the identified cases was knee valgus collapse regardless of what situation an athlete was in on the field. Knee valgus collapse, commonly referred to as "knock knees", is the motion of hip internal rotation and hip adduction and results in the knee joint travelling closer to the midline of the body, interior to the hip and ankle joints (Figure 1.3). 3D model simulations of ACL injury threshold demonstrated that decreases knee valgus angles have been shown to decrease the requisite force required to damage the ACL and shifts of as little as 2 degrees in valgus alignment can reduce the required force by up to 1x bodyweight (Chaudhari and Andriacchi, 2006).

Figure 1.3*: Examples of knee valgus collapse (Contreras, 2013)*

Other high-risk joint positions determined through video analysis of ACL injuries were found to occur when athletes landed with decreased dorsi-flexion and increased hip flexion. Increased hip flexion angle is theorised to increase ACL injury by increasing the gravitational forces acting upon the ACL due to an increased moment arm, caused by the increased distance of the foot from the centre of mass, altering the ACL's contact point of the lateral femoral condyle and increasing the slope of the tibial plateau (Carlson, Sheehan and Boden, 2016). Landing with decreased plantar flexion, leading to a more flat-footed or heel strike landing, locks the ankle into a single position negating the force-absorbing abilities of the calf, achilles and tibialis, thereby passing all the force absorptions directly to the knee (Boden et al., 2009). This is due to a decrease in the landing force energy dispersion between the calf and thighs musculature, due to the lack of motion at the ankle joint, with the quadriceps and hamstrings requiring to produce more force to counteract the reaction force from the ground. The estimated time after contact for ACL injuries to occur was between 17 and 50 milliseconds after initial contact (Krosshaug et al., 2007; Scott 2021).

Combined with video analysis of athletes' ACL injury occurrence, cadaveric assessments have also been used to further the understanding of ACL injury mechanisms by simulating the forces athletes may experience. Kiapour et al. (2016) simulated non-contact ACL injuries via the use of a weight-drop system during landings using cadaver samples and found that knee valgus collapse was one of the primary mechanisms of non-contact ACL injuries. In the specimens, increased knee abduction and internal tibial rotation increased peak ACL strain.

Increased vertical ground reaction forces (vGRF) have been found to be a predictor of ACL injuries. In a retrospective study of 205 female athletes in high ACL injury risk sports, Hewett et al. (2005) found that athletes who went on to injure their ACL had a 20% greater vGRF, during a vertical drop jump task from a 31cm bot, than non-injured athletes. This increase in vGRF also consequently increased knee abduction moments which were found to be 2.5 times greater in the athletes prior to injury.

1.4 Increased Female ACL Injury Risk

One of the most pertinent areas of ACL injury research is in females and the reasons why they suffer higher injury rates than their male counterparts. Female athletes have a 1.7 times greater risk of sustaining an ACL injury during a sporting season compared to male athletes, affecting an estimated 1 in 29 female athletes (Montalvo et al., 2018). This increased risk is accentuated during adolescence with multisport female athletes aged between 13 – 18 having a nearly 10% risk of suffering an ACL injury. Females may be at a greater risk of ACL injury due to anatomical factors. Females on average have a smaller femoral intercondylar notch width and an increased posterior-interior directed slope angle (Sturnick et al., 2015). It has been demonstrated that Males who present a smaller notch width and increased slope angle, similar to those seen in females, are at 1.76 times the likelihood of sustaining an ACL injury compared to males possessing a larger notch width and slope angle thus demonstrating the anatomical factors causing an increased risk of ACL injuries in females (Sturnick et al., 2015).

Females also have a greater Q angle, the angle formed between the quadriceps muscle and the patella tendon and has been shown to be between 2.7 and 5.8 degrees greater in females than males (Khasawneh et al., 2019). This increase in Q angle adds lateral directionality to the quadriceps muscle force predisposing Females to knee valgus collapse due to the increased horizontal force vector produced by the quadriceps (Forcada et al., 2017). The Female hormonal cycle also factors into the increased risk for Female ACL injury. Slauterbeck et al. (2002) found that ACL injuries occur at a significantly higher rate between 1-2 days of starting menstruation. This is theorised to be due to hormonal fluctuations, potentially of the hormone’s oestrogen and progesterone, in the ovulatory phase causing an increase in ligament laxity (the mobility of joints) and therefore decreasing the stability of the knee joint (Herzberg et al., 2017).

Females' landing technique may also play a part in the chance of increased injuries. When comparing Male and Female football players' performance during different landing types, Butler et al (2013) found that females landed with increased dorsi-flexion, increased hip flexion and knee extension moments. All of these variables have been found during video, theoretical modelling and cadaver analysis to be ACL injury risk factors.

1.5 Neuromuscular and Cognitive Factors in ACL Injuries

Neuromuscular control within the body is the interplay between the neurological systems during motor tasks and their biomechanical impacts. During competitions, athletes must process various external factors (e.g. ball and opposition) sending these signals through neurological pathways to perform appropriate motor tasks rapidly to adapt their biomechanics and movements within times often less than a second (Grooms et al., 2015; Mulla and Keir, 2023).

Swanik, (2015) hypothesised that errors in judgment or unanticipated stimuli might cause a momentary loss of situational awareness or startle responses thereby leading to a loss of neuromuscular control and placing athletes into a disadvantageous posture, consequently having to deal with a rapid, premature onset of large joint forces. This is due to a decrease in the force output from the muscles responsible for processing such landing forces like the quadriceps because of the reduction in the amount of time available for the neuromuscular structure to signal for quadriceps contraction to deal with these forces. These unanticipated forces would increase the risk of musculoskeletal injury, and the author recommended conducting future studies to determine the periods in which athletes are most vulnerable due to these cognitive demands.

In sports where ACL injuries are most common such as basketball, volleyball and football, athletes are almost always reacting to intense external disturbances such as an opponent or the ball (Boden et al., 2009). In a study of male and female basketball players, 22 of 28 non-contact injuries occurred within 1 metre of another player. Therefore, Krosshaug et al. (2007) recommended the introduction of distracting elements like those seen in real-match situations to enhance knee control in prehabilitation programmes. These distracting elements would simulate those seen within real ACL injuries and better prepare athletes to process such cognitive stimuli quicker, such as a player within their landing area, in addition to enhancing knee control during such scenarios due to more preparedness for such scenarios occurring which may lessen the effects of such cognitive challenges have on the motor aspect of the movement, in this case, landing mechanics.

Herman et al. (2015) concluded that poor neurocognitive performance either at baseline or in the aftermath of a concussion is associated with an elevated risk of musculoskeletal injury. Factors of neurocognitive performance include visual attention, self-monitoring, agility, reaction time and dual-tasking. They also hypothesised that an increased knowledge of the relationship between neurocognitive factors and musculoskeletal injury would enhance screening, prehabilitation and rehabilitation methods thereby decreasing injury rates.

Swanik et al. (2007) concluded that neurocognitive differences may be associated with the loss of neuromuscular control and coordination errors, predisposing certain intercollegiate athletes to non-contact ACL injuries. In simplified terms, this means that athletes with worse reaction times, processing speed or visual-spatial recognition may expose themselves to a higher risk of injury due to the decreased ability to adjust and perform correct, injury-preventative form. An example of this would be a basketball player jumping for a rebound before the ball has hit the rim. The player must react to the path of the ball in mid-air, catch it, and then land safely. However, athletes with a poor reaction time may react slower, compromising their landing form due to having to adjust mid-air leading to a greater chance of injury owing to a reduced amount of time available to brace for landing (Scott, 2021).

Neuromuscular control can be enhanced with appropriate training leading to a decrease in injury risk factors. In a systematic review of the effects of neuromuscular training, interventions such as dynamic warm-ups, stability exercises and plyometrics enhance the motor control of athletes and can reduce landing injury risk factors, such as single-leg balance and postural control, in relatively short training periods (Akbar et al., 2022). This neuromuscular control training also increased performance variables such as speed, balance and muscular strength with the recommendation that enhancements can be made through a 12-week training block of 3 weekly sessions (Akbar et al., 2022).

1.6. Concept of Dual-Tasking

Cognitive-motor dual-tasking refers to the process of simultaneously managing two tasks, one being cognitive; the processing of new information and one being motor; a specific physical movement. While the mechanisms for dual-tasking’s effect on cognitive-motor tasks are still unclear, three hypotheses have been postulated, as outlined by Leone et al,. 2017) The central capacity sharing model theorises that dual-tasking performance is limited by their capacity to allocate appropriate attentional resources to two tasks simultaneously, therefore distributing the attentional capacity between the two tasks (Friedman et al,. 1982); 2) The bottleneck model, which is based on the theory that certain tasks must be carried out successively, not simultaneously, so a bottleneck occurs when the information from two different tasks are processed by the same or similar neurological networks (Pashler, 1994); 3) The cross-talk model which proposes that if two tasks use similar neuronal populations they will not disturb each other (Navon and Miller, 1987).

Dual tasking will typically impair the motor control requirements while simultaneously performing two tasks. Healthy older adults were found to sacrifice balance performance and gait control when performing a variety of motor tasks (de Barros et al., 2021). This decrease in movement performance does however seem to be improved with dual-task training. Older adults who undertook dual-task training were found to walk significantly faster than untrained adults undertaking the same scenarios. These training improvements in motor control were present after a total of just six 45-minute sessions and maintained this increased motor control 12 weeks post-training (Silsupadol et al., 2009). Improvements in dual-task performance can also be influenced by people’s habits and activities. Maden et al. 2022 found that individuals who play video games for more than 2 hours per day had improved cognitive function and decreased dual-task interference when compared to non-gamers during a dual-tasking walking scenario.

Cognitive performance impairments have also been observed during dual-tasking studies within athletes. Laurin and Finez (2019) observed that the more difficult the numeric calculation, the greater the cost in performance when performed simultaneously with juggling. This motor task cost may also be trainable, with experts in the tasks performed during a dual-tasking scenario experiencing less of a negative impact on cognitive performance than that of novices due to a higher working memory capacity and an increase in attentional control (Moreira et al., 2021). This may indicate that experienced athletes within a sport may see less detrimental effects to motor tasks such as landing whilst performing dual tasking as compared to novice counterparts. It has already been shown that experienced Volleyball players have been shown to experience the same ground reaction forces and rates of loading during spike and blocking jumps when compared to novices, this is despite jumping higher, suggesting their experience with the movements better enables them to reduce the risks of injuries in such jumps (Garcia et al., 2022). The combination of improved motor control and decreased motor task cost warrants further investigation and investigating the effects of differing stimuli on novice and experienced groups using a methodology similar to the one used within this study may provide insight into such within ball sports such as Basketball and Netball.

Table 1.6 displays all identified studies found via database and registry search investigating the effect of dual-tasking on landing mechanics. 13 studies were identified as relevant and involved a dual-tasking scenario while investigating the kinematics and kinetics of landings. As shown, all of the 13 studies investigated dual-tasking with stimuli presented through a visual medium and a review of unplanned athletic movements by Giesche et al. 2021, including both landing and cutting tasks, found that all studies presented tasks visually. All studies in Table 1.6 found alterations to landing mechanics in at least one variable, with increases seen in both total force (n = 6) and knee abduction angles within the 13 studies (n =6).

Stimulus timing of the cognitive component seems to have no effect on landing mechanics with Shunya et al. (2011) and Brown et al. (2009) finding no intra-timing differences between groups despite all exhibiting increased ACL injury risk factors. This was in addition to the comparisons between easy and more challenging cognitive tasks showing no significant differences between one another. The current body of literature indicates that the presence of dual-tasking regardless of difficulty and presentation time is enough to alter landing mechanics.

Table 1.6: Characteristics of dual-tasking movement task studies, stimulus types and their outcomes (n = 13)

Study	**Participants**	**Movement Task**	**Conditions**	**Outcomes**
Almonroeder et al., (2018)	• N = 20 females • Aged 18 – 25 years • Basketball players	• Vertical drop jump (VDJ) with overhead goal (OG), decision making (DM) and OG+DM conditions. • Participants dropped from a 31cm box onto force plates 15cm away	• **Visual (light) stimulus** • Stimulus presented ~250ms prior to ground contact	• Greater peak knee abduction angles in the DM, OG, and OG + DM conditions • Higher vertical ground reaction force (vGRF) and lower knee flexion angles during the OG and OG+DM conditions

Study	**Participants**	**Movement Task**	**Conditions**	**Outcomes**
Brown et al., (2009)	• N = 26 (13 males, 13 females)	• 2m forward jump with single-leg landing followed by horizontal cut under anticipated and unanticipated conditions • The unanticipated condition involved a single-leg jump with the landing leg determined by the visual stimulus	• **Visual (light) stimulus** • Stimulus given at 400, 500 and 600ms before initial ground contact	• Increased hip and knee internal rotation moments during unanticipated landing conditions

Study	Participants	Movement Task	Conditions	Outcomes
Dai et al., 2018	• N = 38 (19 males, 19 females) • (age 21.4 ± 1.4 years) • Recreational athletes	• VDJ from a 30cm box under 3 conditions: baseline, counting backwards in 1s, counting backwards in 7s from a random number	• **Visual stimulus + Cognitive task** • Stimulus presented immediately before initiating jump landing	• Participants demonstrated decreased knee flexion angles and maximum jump height in both counting conditions • Participants also exhibited increased vGRF in both counting conditions
Gieschen et al., (2020)	• N = 20 males • (age 27.1 ± 4.2 years) • Could perform counter movement jump (CMJ) of over 30cm	• CMJ from a 30cm box with single-leg landing • Landing leg was determined under either planned or unplanned conditions	• **Visual (light) stimulus** • Landing leg presented ~380ms prior to landing	• Increased centre of pressure path length during unplanned landings

Study	Participants	Movement Task	Conditions	Outcomes
Herman et al., (2016)	• N = 20 high cognition and 17 low cognition participants • Aged 18 – 30 years • Recreational athletes	• Unplanned forward/vertical jump following a drop from a 30cm box • Direction of the second jump was shown as an arrow on a screen in front of participants	• **Visual (arrow) stimulus** • Second landing location indicated ~250ms before initial landing	• Lower performance group demonstrated increased pGRF, tibial shear force and knee abduction angle
Imai et al., (2022)	• N = 20 females • (20.2 ± 1.3 years) • Collegiate athletes	• VDJ from a 30 cm box under single and dual-task conditions • Dual tasking condition was the addition of two 2 digit numbers	• **Visual (light) stimulus + Cognitive task** • Stimulus given immediately prior to DVJ	• Greater vGRF and peak knee abduction moments in the dual-tasking condition

Study	**Participants**	**Movement Task**	**Conditions**	**Outcomes**
Kajiwara et al., (2019)	• N = 20 (10 males, 10 females) • (age 20 ± 1.1 years) • University level athletes	• Single-leg drop landing from a 30cm platform. • Single-task and dual-task setup. A Stroop test gave the corresponding coloured landing location during dual-tasking condition	• **Visual (light) stimulus** • Landing location was indicated as soon as participants dropped from the platform	• Dual-tasking condition increased internal tibial rotation angle and vGRF

Study	**Participants**	**Movement task**	**Conditions**	**Outcomes**
Kipp et al., (2013)	• N =30 females • 12 recreationally active (19.7 ± 1.7 years) • 18 NCAA D1 athletes (19.8 ± 1.2 years)	• Single-leg landing from atop a 30cm box followed by a 90-degree cut to the opposite direction of the landing leg under anticipated and unanticipated conditions. • The unanticipated conditions landing leg was presented via a visual stimulus	• **Visual (light) stimulus** • Stimulus given ~350ms before landing	• The unanticipated condition had greater knee abduction only in the recreationally active participants

Study	**Participants**	**Movement Task**	**Conditions**	**Outcomes**
Lapointe et al., (2018)	• N =20 • 9 athletes with a history of concussions (4 male,5 female) • 10 control (6 males, 4 females) • Aged between 18 – 26 years	• Forward jump over a box into a single leg landing upon the participant's dominant leg followed by a cut to either the left or right under anticipated and unanticipated conditions. • The unanticipated conditions cut direction was given via arrows, simultaneously giving the direction either congruently or incongruently	• **Visual (arrows) stimulus** • Stimulus given ~500ms before landing	• The concussion group demonstrated decreased knee varus

Study	Participants	Movement Task	Conditions	Outcomes
Mache et al., (2013)	- N = 29 (16 males, 13 females) - (age 22 ± 3 years) - Recreational athletes	- Participants hung from a bar positioned 20% above their height. They then performed either a planned or unplanned landing or drop jump	- **Visual (light) stimulus** - Unplanned landing or jump indicated ~250ms before prior to landing	- Unplanned jumps led to an increase in knee abduction angle and a decrease in knee and hip flexion angles
McLean et al., (2010)	- N = 20 females - (19.2 ± 1.7 years) - NCAA D1 athletes	- Forward jump with single-leg landing cutting to the opposite direction of landing leg under anticipated and unanticipated conditions	- **Visual (light) stimulus** - Stimulus given ~650ms before landing	- The unanticipated condition experienced increased peak knee abduction moments

Study	**Participants**	**Movement Task**	**Conditions**	**Outcomes**
Schnittjer et al., (2020)	• N = 20 (10 males, 10 females) • (age 22.4 ± 0.42 years) • Recreational athletes in jumping sports	• Tuck jumps performed for 10 seconds under either single-task, easy dual-task, and difficult dual-task conditions. • The easy dual-task consisted of a 5-digit recall. The difficult dual-task a 5-digit summation.	• **Visual (light) stimulus + Cognitive task** • The 5 digits were shown throughout the 10 seconds	• Both dual-tasking conditions led to a decrease in movement quality of tuck jumps

Study	Participants	Movement Task	Conditions	Outcomes
Shinya et al., (2011)	- N = 20 males - (age 24.4 ± 3 years) - Recreationally active	- Small vertical jump into a single-leg landing under single and dual-task conditions - Dual-task conditions involved pressing a corresponding button to the visual stimulus displayed	- **Visual (light) stimulus** - Presented under 4 conditions at 0, 100, 200 and 300ms after take-off	- Maximum vGRF increased in dual-tasking conditions regardless of stimulus timing
vGRF = vertical ground reaction force, VDJ = vertical drop jump, OG = overhead goal, DM = decision making, CMJ = counter-movement jump				

2. Purpose of Study

Motor-cognitive dual-tasking has been shown in previous studies to alter the landing biomechanics of athletes, placing them into landing positions that may potentially lead to an increased risk of non-contact ACL injury. However, all previous research has performed the cognitive aspects of dual-tasking through only a visual medium. During real competition, athletes must not only process visual stimuli but also auditory, be it a team mate calling for the ball or a referee's whistle.

Thus, the purpose of this study is to investigate the effects of the same cognitive task presented through visual, auditory and a combination of both stimuli simultaneously to compare the effects on both the cognitive and motor tasks performed. It was hypothesised that the ACL injury risk factors measured, peak ground reaction force, peak knee flexion angle and peak knee valgus angle, would be altered with predicted increases in landing force and knee valgus collapse during landing.

3. Methodology

3.1 Participants

30 total participants (20 Male and 10 Female) were recruited for the study which consisted of 1 lab visit of approximately 45 minutes. Participants were recruited from the university student base and the general public. To participate they must have been between the ages of 18 – 35 years old. Participants must also have been classified as physically active as per the UK government guidelines (> 150 minutes of moderate physical activity) (GOV.uk). Participants had to be free from any major lower limb or trunk injury within the previous 12 months. Participants also had to be free from any cognitive disorders which would impair their ability to respond to any auditory or visual stimuli. Due to technical malfunctions with the equipment, of the 30 participants who completed the study, the Time to Pass (TTP) and peak Vertical Ground Reaction Force (pVGRF) data could not be recorded on 6 occasions. However, their peak Knee Valgus Angle (pKVA) could still be obtained and used for statistical analysis and were as such kept in the study.

Table 4.1: Male and Female participants total variables measured and body mass (Mean ± SD).

Measurement	**Total Male Participants**	**Total Female Participants**
Peak Knee Valgus Angle (pKVA)	20	10
Peak Vertical Ground Reaction Force (pVGRF)	15	9
Time to Pass (TTP)	15	9
Passing Direction & Errors	20	10
Body Mass (Kg)	85.2 ± 15.1	64 ± 7.2

3.2 Initial Assessment

Prior to participation, subjects were sent a participant information sheet detailing information such as the aims, risks, and procedures of the study before the assessment day. Participants were also sent a video demonstration of the experimental procedures to confirm whether they would be safe and comfortable completing the drop landing task required. On the day of the assessment, before the experiment began, participants were asked to complete both a risk assessment and consent form. The consent form and participant information sheet were both based on the guidelines used by the Lancaster Medical School. The risk assessment form was an adapted version of one used during the Sports Science course for sub-maximal exertion tasks.

3.3 Ethical Approval

Ethical approval was given by the Lancaster University Medical Schools Research and Ethics Committee, this included the study design as well as all related materials such as forms and promotional material. All participants' data was anonymised, and they retained the right to withdraw at any time.

3.4 Testing Protocol

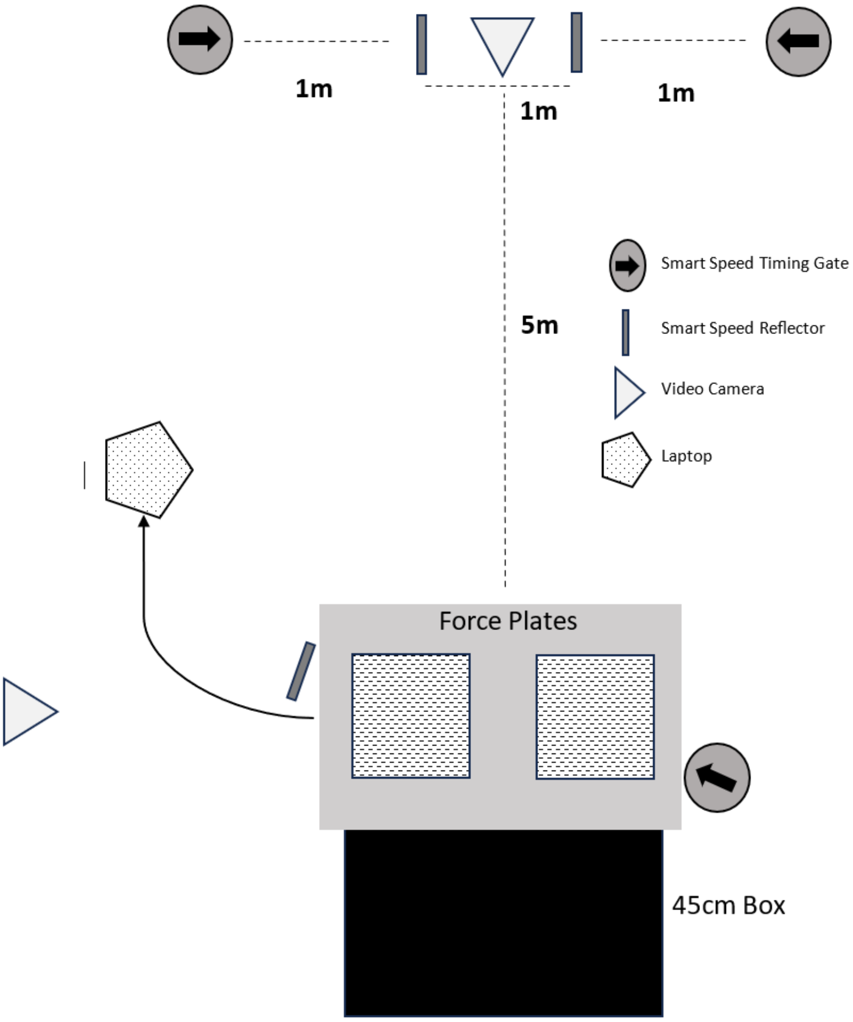


Figure 3.4.1: Schematic diagram of the experimental set-up.

Participants were instructed on the testing protocols through a verbal explanation before being given a visual demonstration of the technique they would be using during the experiment. Participants were to start the test atop the 45cm box, which was positioned approximately 10cm horizontally away from the force plates. The height of the force plates (5cm) on the floor below meant that the total height dropped was 40cm. The investigator then demonstrated a step-off technique vertical drop landing onto the vertical axis force plates (PS2141 Pasco, California, USA) below, which were cased within a custom wooden housing.

Participants were to perform the step-off technique with the same leg each time to keep both landing mechanics (Lawson et al., 2022) and the stimuli trigger point consistent throughout the trials.

Participants then completed both static and dynamic calibration tasks for the video capture system. For the static calibration, participants stood upon the force plates in anatomical position to record body mass measurements and to confirm the framing of the Camera (RX10, Sony, Minato, Japan) used for the capture of their frontal plane. For the dynamic calibration, participants performed a drop landing from the 45cm box, passing the ball to a pre-determined direction to calibrate both the Smart Speed Timing Gate and Reflector (Smartspeed, Vald Performance, Queensland, Australia) used to trigger the stimuli and insure its consistent presentation of stimuli, as well the camera capturing the sagittal plane used to capture both peak knee flexion angle and the time taken to pass the ball.

Participants would perform a vertical drop landing followed by a Netball style chest pass under the following conditions:

- **Control**: The participants were verbally delivered the passing direction of their next trial before stepping upon the box. No stimuli were given from the timing gates

- **Light**: The participants were given a visual stimulus that lasted indefinitely. The timing gates red, blue, and green 13 x 8mm LEDs provided the visual stimulus

- **Sound**: The participants were given an auditory stimulus that lasted approximately 1 second from the corresponding directions timing gate unit. The timing gates 90dB buzzer gave an auditory stimulus.

- **Light & Sound**: The participants were given both the visual stimulus and audio stimulus simultaneously.

Stimuli for participants were given at 50-100ms before landing upon the force plates and were triggered by the breaking of a beam from the timing gates positioned on the edges of the force plates' wooden housing. The amount of time a participant had to respond was calculated using video analysis during the pilot testing.   The position of the stimulus-triggering timing gates was kept consistent across all participants. Participants were given a familiarisation period before each condition, in which they were given as many attempts at the upcoming condition as to feel comfortable, before giving a verbal command to begin the recorded testing process. Participants were given the opportunity to take rest periods, if required, at any point during the testing protocol.

Participants were to perform 8 successful passes in total, which were to include 4 passes to both the left and right. The passes mimicked a stationary chest pass seen in netball and were designed to simulate the stimuli players experience after jumping to gain possession of the ball. Passing direction was pre-determined through the use of a random number generator and inputted before each repetition using the Smartspeed Android application (Smartspeed, Vald Performance, Queensland, Australia), but was unknown to the participant under all but the Control condition. Any trials in which the participant passed in the incorrect direction were recorded. All incorrect pass directions were repeated in the same order they occurred in, with 4 successful passes to both the left and right required to complete the trial (E.g., if a participant failed repetition 3 =L, 4 = R, 7 =L they would perform the additional repetitions in the subsequent order of 9 = L, 10 =R, 11 = L). Note that participants were not informed of this detail beforehand. All incorrect attempts were kept in the subsequent data analysis as they provided insight into how the differing difficulties of the cognitive stimuli may change landing mechanics and the time to pass.

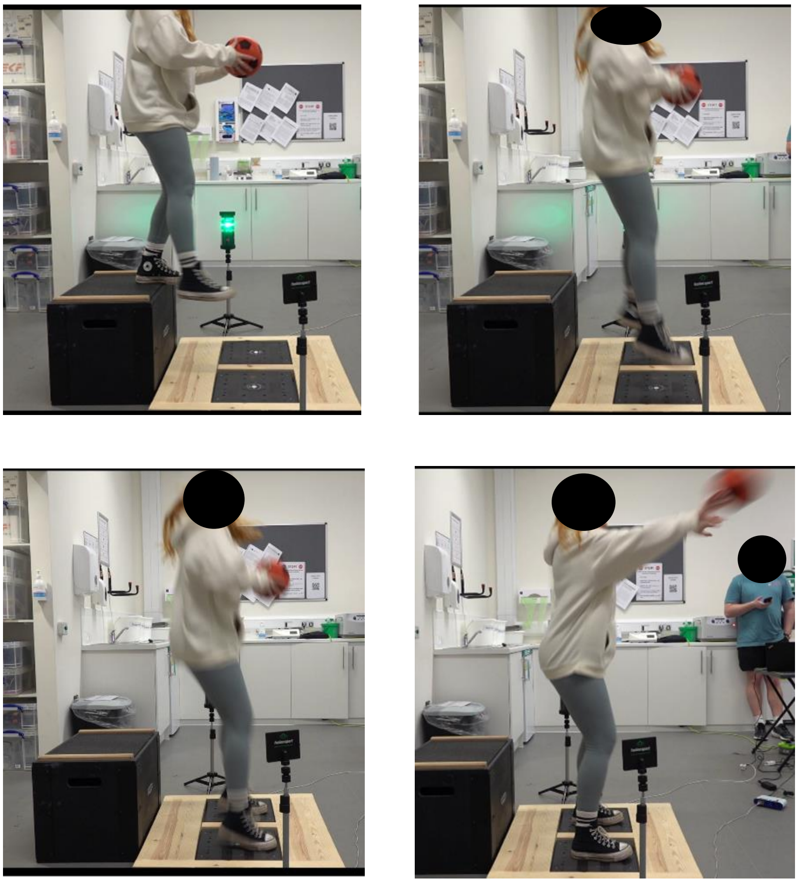


Figure 3.4.2 A demonstration of the Drop Landings key stages. *Top Left: Pre-drop landing. Top Right: Stimulus trigger point. Bottom Left: First point of ground contact and beginning of time to pass measurement (TTP). Bottom Right: Last frame of ball contact and end of TTP measure.*

As shown in Figure 3.3.2, participants' Time to Pass (TTP) was measured as a means of assessing the impact that differing stimulus types would have in realistic sporting scenarios. The TTP was calculated as the time it took for the participants to land and release the ball. The point of landing was the first frame in which at least one leg was in contact with the force plates below. The point of release was deemed as the first frame in which none of the participant's body was in contact with the ball. The total amount of frames was calculated using Adobe Premiere Pro (Adobe, USA) custom presets. All passing directions and errors were recorded during the session and confirmed through video analysis. The height of the camera used to measure both TTP and and peak knee flexion angle were determined on a per-participant basis with the framing such as to ensure foot contact and release of the ball could be seen throughout the movement.

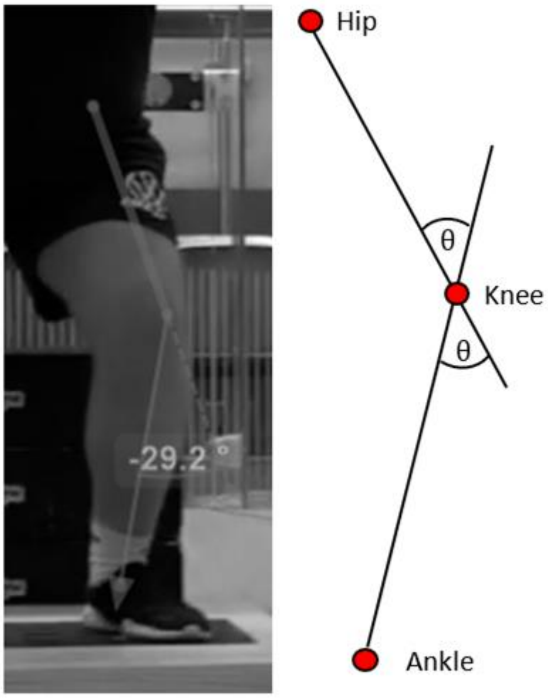


Figure 3.4.3: Peak Knee Valgus angle measurement methodology in Kinovea and sketch demonstration. *θ = Peak Knee Valgus Angle value.*

Knee Valgus angle was measured from raw footage from the video recordings with a peak depth of the descending portion of the landing (prior to the participant's ascending motion to pass the ball) used as the measurement point. The image file was then exported to the open source software program Kinovea (Version 0.94) where all angles were measured. Joint centres of the hip, knee and ankle were identified with digital marker points placed upon them in Kinovea (Mclean et al,. 2005). Joint centre positions followed the methodology of Schurr et al, (2017) and Wilson & Davis, (2008) in which the three points measured were: one bisecting the malleoli of the ankle (ankle), one bisecting the femoral condyles (knee), and one on the proximal thigh parallel to the anterior superior iliac spine (hip). Kinematic data from the frontal plane was collected at 50 frames per second from a Sony RX10 camera 5m in front of the participants, at a height of 55cm. This height was chosen to be closest to 0 degrees above the participant's knees as it has been shown to yield the closest results to 3D coordinate systems in knee abduction angles (Englander et al., 2019). All measurements were obtained by a single investigator who demonstrated high levels of intra-rater reliability between repeat measures when assessing the same pKVA measurements one week apart (Straub & Powers 2022). Video capture for both the frontal and sagittal planes was recorded at 50fps. Adobe Premiere Pro processed video files and was used to export the images of peak knee valgus to Kinovea (0.94).

Video analysis of the peak Knee Flexion was measured from the footage recorded in the sagittal plane, also used to measure participants TTP, from the participant's left side and analysed using Kinovea (0.94). The maximum flexion point was identified visually and defined as the frame where no more downward motion occurred at the hip, knee, or ankle joints (Dingenen et al., 2014). The knee flexion angle was calculated as the angle between a line formed from the digital marker points placed between the greater trochanter and the femoral condyle and a line between the femoral condyle and the lateral malleolus. This was the methodology used in previous research to validate the reliability of Kinovea to analyse peak knee flexion and valgus angle during counter-movement jumps from a box like the design used within this study. It was found that such measurements were highly reliable when compared to 3D analysis when taken at peak flexion angle, as was done in this study (Howe et al., 2020). Previous research into the validity of 2D analysis of peak knee valgus and peak knee flexion angle during single leg squats using Kinovea has also found moderate and strong correlations when compared to 3D motion analysis, which is considered the “gold standard” (Schurr et al., 2017). This ability to measure such values during landing allows research, such as the one in this study, to be carried out at relatively low costs and greater flexibility due to the differences in recording setups required between the two methods.

Data capture for the force platforms was performed using Capstone software (PASCO Capstone version: 2.3.1, PASCO scientific, California, USA) and collected at 1000Hz (Niu et al,.2014). Force data was then exported and analysed in Microsoft Excel (Microsoft, USA) to identify the peak landing force of both legs before being normalised and expressed as a multiple of the participant's body weight (xBW). The force plates were housed within a custom wooden casing making it easier for participants to land on them as well as improving the accuracy as has previously demonstrated in anchoring force plates during vertical drop jumps (Sands et al., 2020). The force plates had value range of between -1100N to 4400N (Hanna, 2024) .

Dominant and non-dominant legs were also measured when assessing peak ground reaction force. The dominant leg of participants was determined on a per-attempt basis, with the leg experiencing the greater force being denoted as the dominant leg for that specific attempt.

3.5 Statistical Analysis

Statistical analyses were performed using SPSS software (IBM Corp. Released 2022. IBM SPSS Statistics for Windows, Version 29.0. Armonk, NY: IBM Corp). To assess the statistical significance of our findings, two-tailed dependent t-tests were employed. The level of significance was set at $p < 0.05$. Prior to conducting the t-tests, the normality of data distribution was verified using the Shapiro-Wilk test. All datasets successfully met the criteria for normality, validating the use of parametric tests. The Holm-Bonferroni correction was applied to the results of the dependent t-tests to account for the increased likelihood of a type I error when performing multiple comparisons. Effect sizes were calculated to quantify the magnitude of observed phenomena. These were interpreted as small ($d < 0.2$), medium ($d = 0.2 - 0.5$), and large ($d > 0.5$) (Cohen, 1988).

A power analysis was carried out prior to testing using G*Power (Version 3.1.9.7) to determine the minimum sample size required, which was determined to be $n=23$.

4. Results

4.1 Peak Knee Flexion Angle

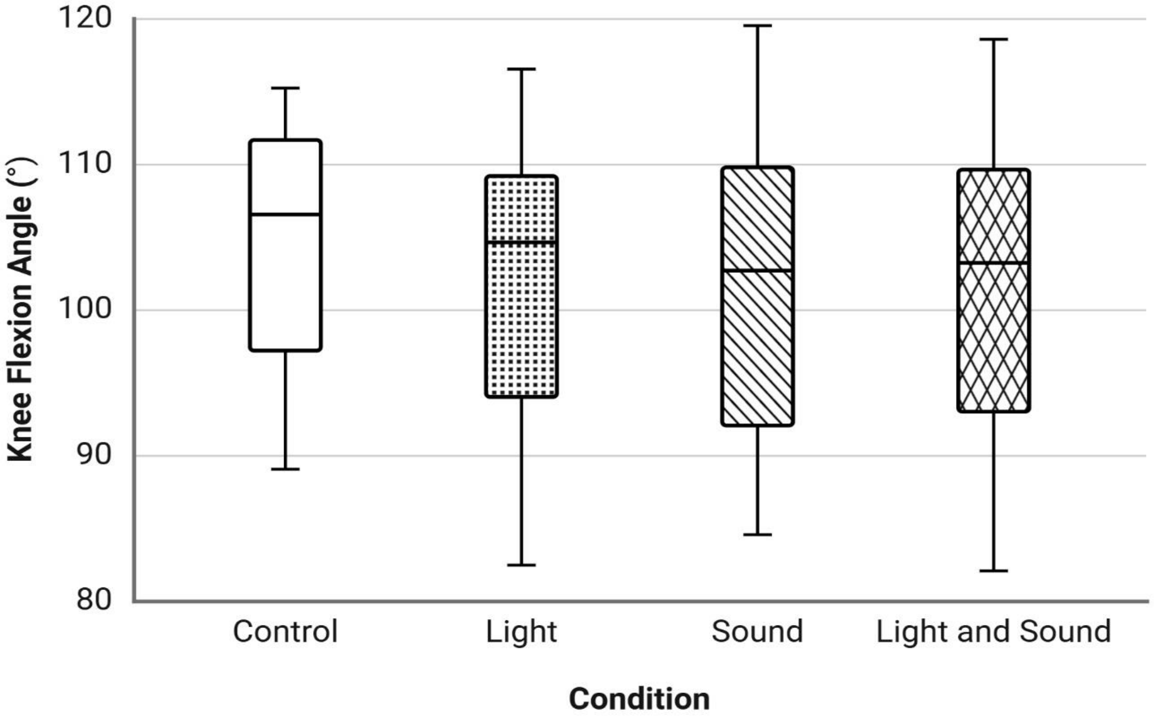


Figure 4.1: Box plot of Peak Knee Flexion Angle (°) during the four conditions (n =24).

There was found to be no statistical difference between the Peak Knee Flexion Angle in any of the conditions (n=24, Control: 104.4 ± 8.37°, Light: 101.8 ± 10.1°, Sound: 101.5 ± 10.3°, Light & Sound: 100.9 ± 10.5°). Unlike peak Knee Valgus Angle, Males and Females were analysed as a combined group as there was no significant difference in peak Knee Flexion Angles measured between the two sexes within conditions. In addition, previous research has been mixed as to the effect sex has on peak Knee Flexion Angle during Drop Landings when compared to the more conclusive differences seen in peak Knee Valgus Angle (Huston *et al.*, 2001; Ishida *et al.*, 2018; Yi, Park and Lee, 2004).

4.2 Time To Pass (TTP)

There was a statistically significant difference between the Sound (946.4 ± 481.1ms) stimulus and the Control (616.3 ± 209.1ms, $p < 0.005$), Light (690 ± 195.9ms, $p < 0.012$) and Light + Sound (657.5 ± 207.0ms, $p < 0.006$) as well as a significant difference between the Control and Light Conditions ($p < 0.048$). There were no significant differences between the light and sound conditions with either the Control or Light Conditions. (Figure 4.2.1).

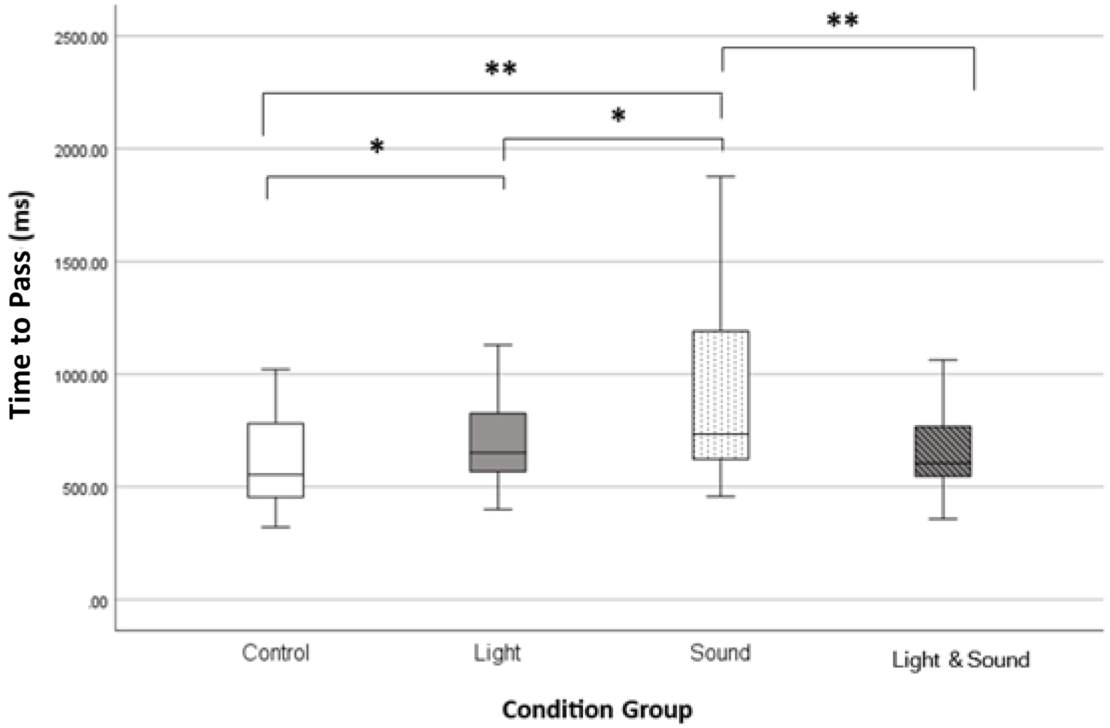


Figure 4.2.1: Time to Pass differences between condition groups (n=24). *Significance levels indicated by (* $p < 0.05$, ** $p < 0.01$)*

Of the 24 total participants for which reaction time data was recorded, 21 participants had at least 1 failed trial and therefore qualified for analysis comparing correct vs incorrect trials during the sound condition, with an average of 3.1 incorrect trials per participant. The statistical significance of this condition may however be skewed by the participants who had a greater reaction time during incorrect attempts as illustrated in Figure 4.2.2.

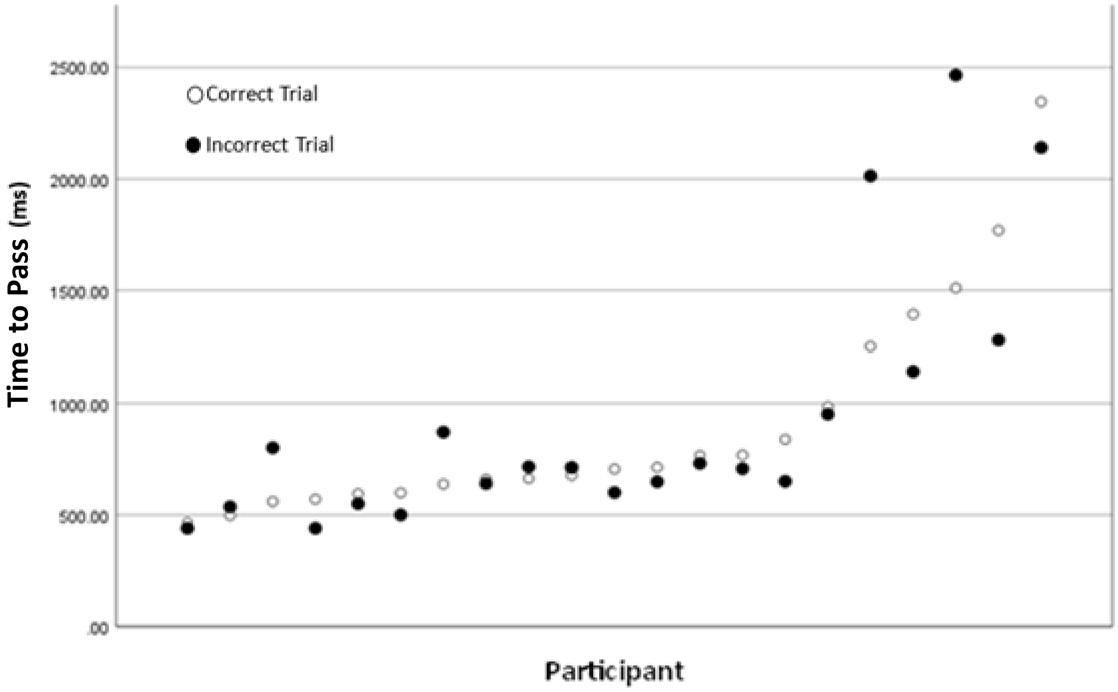


Figure 4.2.2: Time to Pass of Correct and Incorrect attempts during Sound Condition of all applicable participants. *(n = 21)*

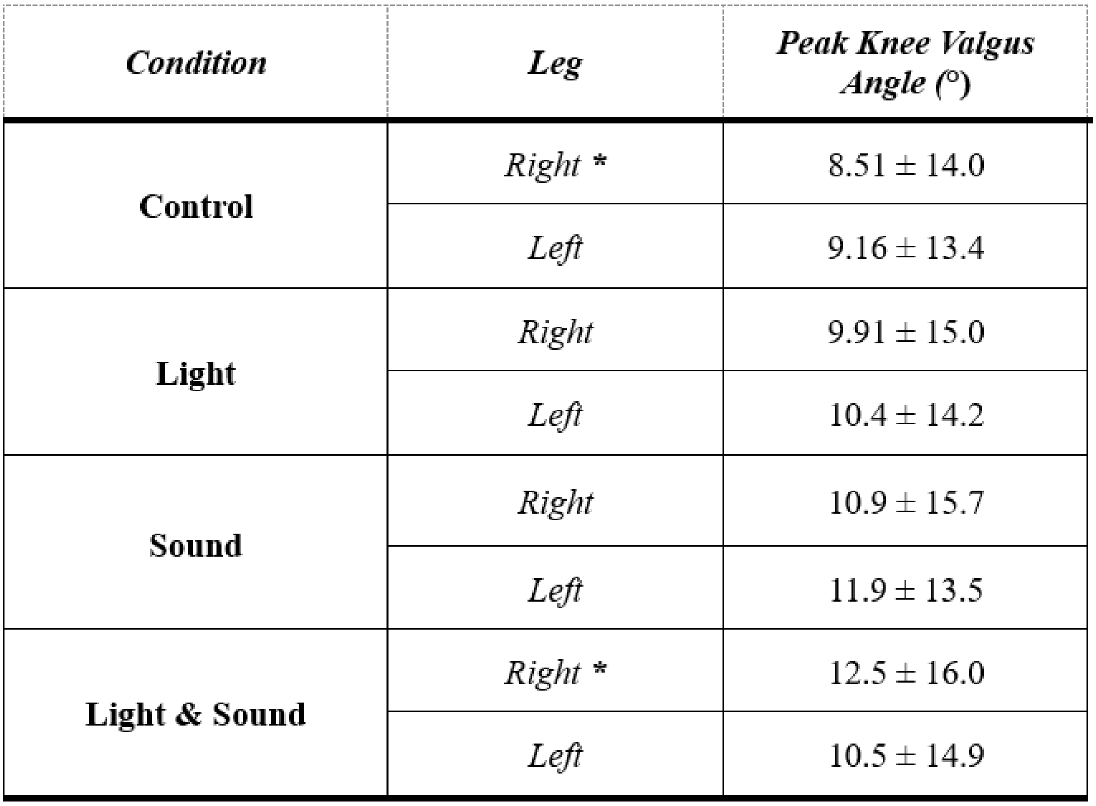
During the Sound condition, there was a statistically significant difference between when participants correctly or incorrectly identified the direction to pass the ball (903 ± 484 vs 930 ± 577 ms, $p < 0.01$). (Table 4.2). These incorrect attempts will have increased the TTP time for the sound condition as both correct and incorrect attempts were left in to better illustrate the TTP that occurred during the Sound condition.

Table 4.2: Differences mean Time to Pass ± SD and Total Number of Attempts in Correct and Incorrect Conditions. *(n = 21). p value indicates the difference between Correct and Incorrect attempts. Asterisks indicate the significant differences between the conditions (** p < 0.01)*

Condition	***Time to Pass (ms)***	***Total Number of attempts***
Correct **	903 ± 485	168
Incorrect **	930 ± 578	66

4.3 Knee Valgus Angle (KVA)

Table 4.3.1: Mean Peak Knee Valgus Angle (°) ± SD in relation to the Condition and leg measured in all participants (n = 30). *p value indicates the difference between Peak Knee Valgus Angle (* p < 0.05)*



Condition	*Leg*	*Peak Knee Valgus Angle (°)*
Control	*Right **	8.51 ± 14.0
	Left	9.16 ± 13.4
Light	*Right*	9.91 ± 15.0
	Left	10.4 ± 14.2
Sound	*Right*	10.9 ± 15.7
	Left	11.9 ± 13.5
Light & Sound	*Right **	12.5 ± 16.0
	Left	10.5 ± 14.9

Table 4.3.1 displays the Peak Knee Valgus Angle (pKVA), measured in degrees, of the 4 test conditions for participants' right and left legs. Participants experienced a statistically significant increase in pKVA of 4 degrees in their right leg when comparing the control to the Light & Sound condition (p = 0.042). The effect size was 0.54 indicating a moderate difference between the samples.

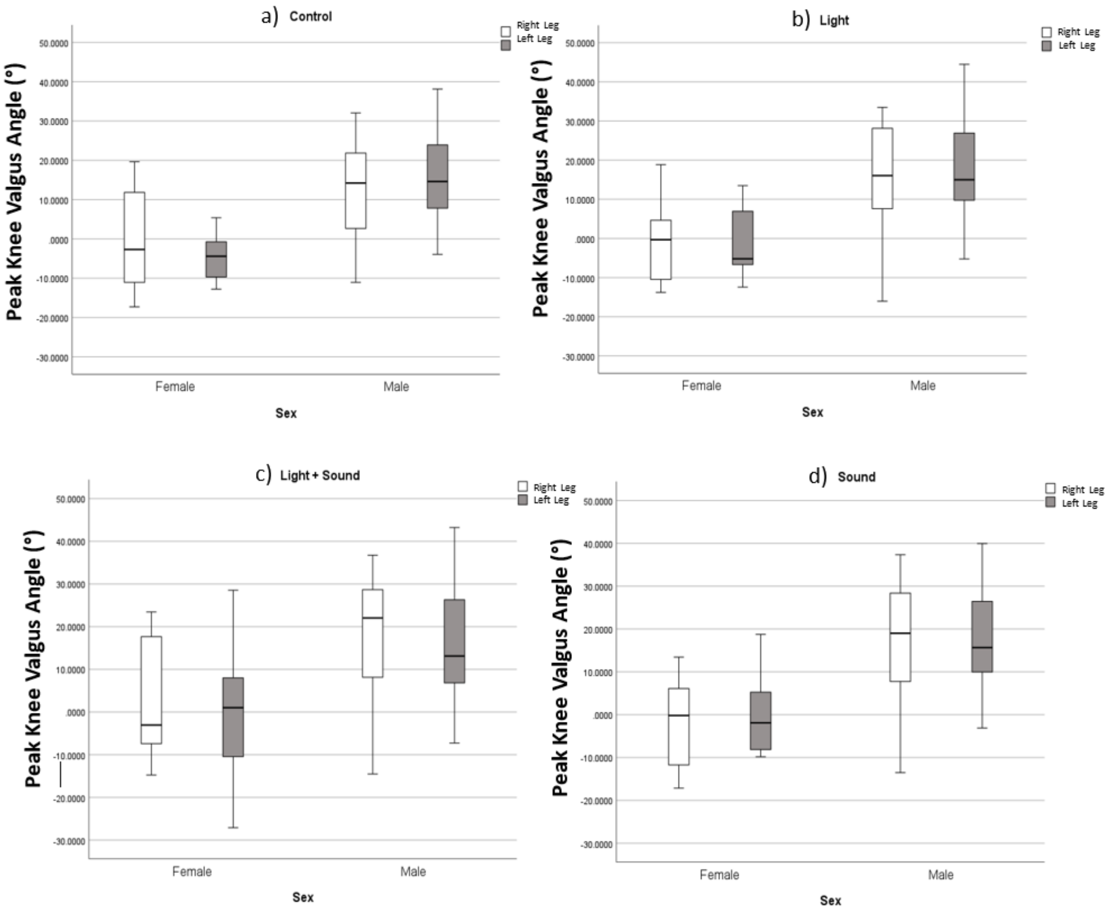


*Figure 4.3: **Peak Knee Valgus Angle (pKVA) of the Right and Left leg separated by Sex.** (n = 30). a) Control condition. b) Light Condition. c) Sound Condition. d) Light & Sound Condition.*

Due to the earlier outlined differences between males and females affecting pKVA, they were also analysed separately. There were found to be no statistically significant differences due to the changes in stimulus type in either the Male (n = 20) or Female (n = 10) groups. The closest to statistical significance was in males between the Control and Light & Sound conditions, which following Holm-Bonferroni corrections narrowly missed significance (p = 0.054) in showing an increase in peak knee valgus, suggesting a more varus landing style.

Table 4.3.2: Mean Peak Knee Valgus Angle ± SD in relation to the Condition and leg measured among Male and Female Participants (n = 30). *p value indicates the difference between Correct and Incorrect attempts. Asterisks indicate the significant differences between the conditions (* p < 0.05)*

Sex	*Condition*	*Leg*	*Peak Knee Valgus Angle (°)*
Male ***(n =20)***	**Control**	*Right*	13.3 ± 12.2
		Left	15.3 ± 8.46
	Light	*Right*	15.0 ± 10.3
		Left	16.3 ± 8.94
	Sound	*Right*	17.0 ± 10.6
		Left	17.7 ± 9.22
	Light & Sound	*Right*	17.6 ± 14.1
		Left	15.4 ± 15.5
Female ***(n = 10)***	**Control**	*Right*	- 1.00 ± 12.5
		Left	- 3.18 ± 11.0
	Light	*Right*	- 0.36 ± 14.5
		Left	- 1.54 ± 12.6
	Sound	*Right*	- 1.42 ± 14.3
		Left	- 0.12 ± 11.3
	Light & Sound	*Right*	2.36 ± 14.7
		Left	0.76 ± 12.3

4.4 Peak Ground Reaction Force in the right and left leg

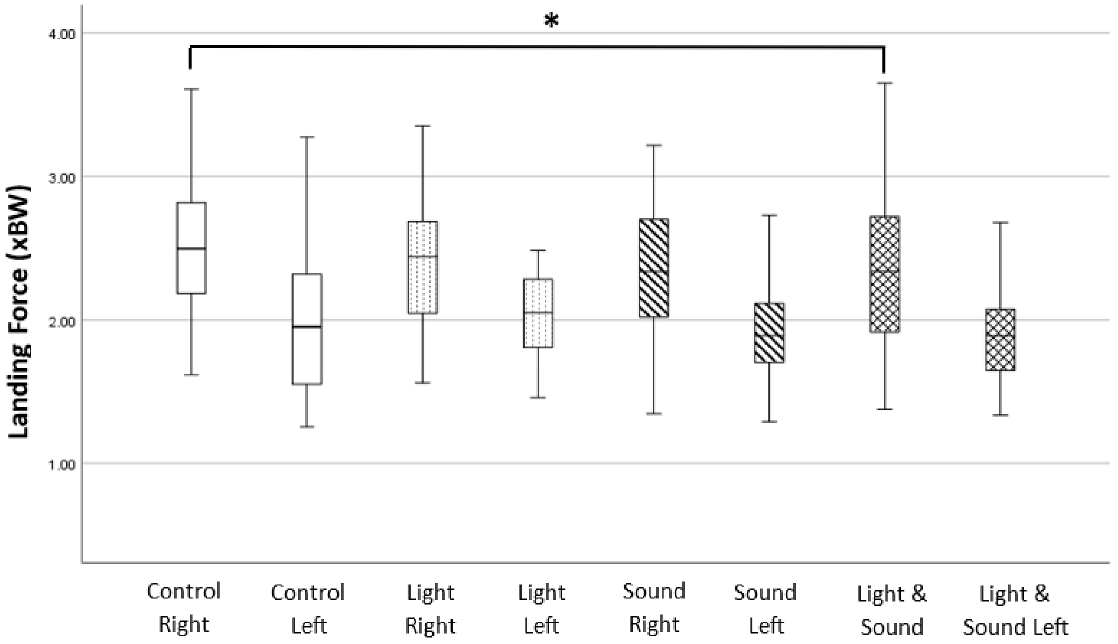


Figure 4.4.1: Box plot of mean landing force relative to body weight for participants' Right and Left legs during the four conditions (n =24). *p values indicate the differences between conditions in landing forces when compared against the same leg (* p < 0.05)*

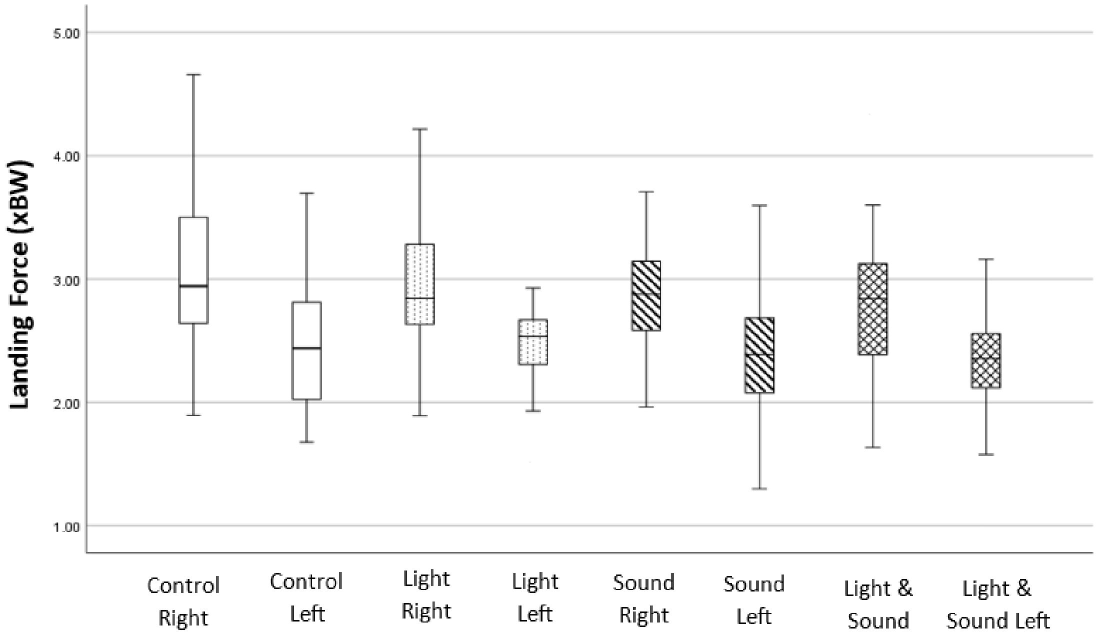


Figure 4.4.2: Box plot of maximum landing force relative to body weight for participants' Right and Left legs during the four conditions (n =24).

Figure 4.4.1 displays the box plots of the participant's (n = 24) mean landing force for the different conditions, expressed as a multiple of their body weight (xBW). There was evidence of a statistically significant decrease in the right leg landing force from the Control condition (2.50 ± 0.526) to the Light & Sound condition (2.32 ± 0.556, p = 0.042) following the Holm-Bonferroni correction.

Individuals' single maximum landing force was also analysed and displayed in Figure 4.4.2. There were found to be no statistical differences between any of the participant's maximum landing force, however the control (3.03 ± 0.660) and light and sound (2.78 ± 0.507, p = 0.054) once again approached statistical significance following Holm-Bonferroni correction.

4.5 Peak Ground Reaction Force in Dominant and Non-Dominant legs

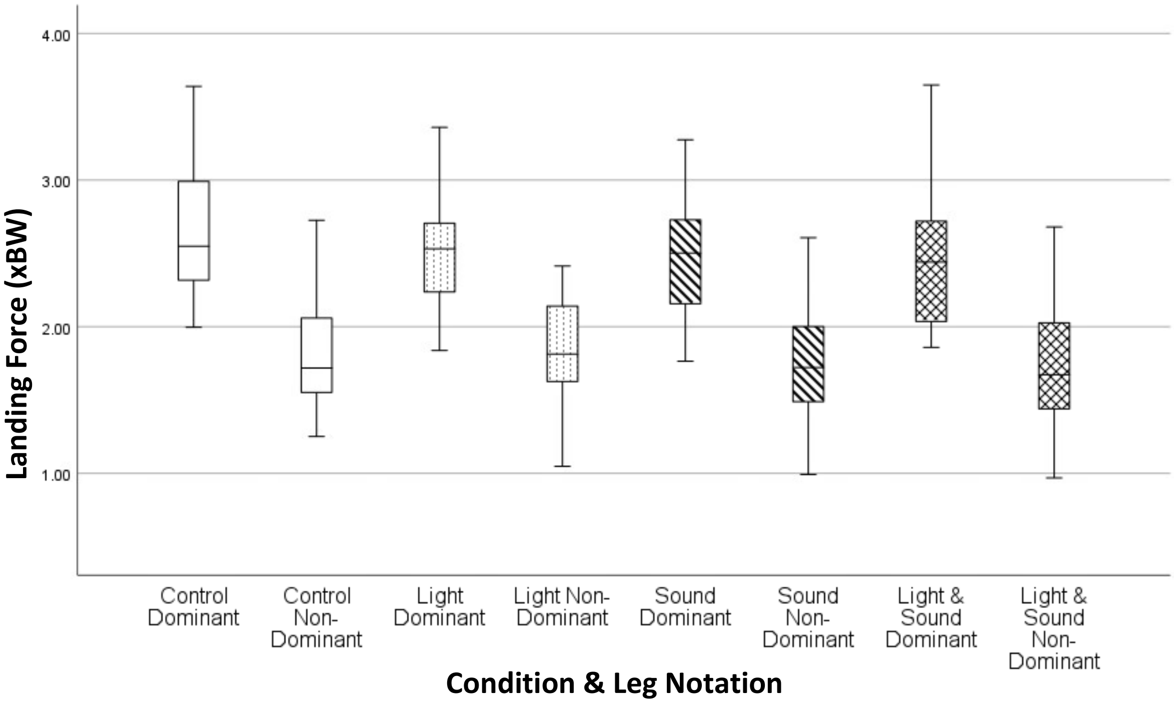


Figure 4.5.1: Box plot of mean landing force relative to body weight for participants' Dominant and Non-Dominant legs during the four conditions (n =24).

There was found to be no statistically significant difference between the mean landing force in either participant’s dominant or non-dominant legs between conditions. Participant’s dominant Control (2.64 ± 0.440) approached statistical significance with both the Sound (μ = 2.44 ± 0.380, $p = 0.072$) and Light & Sound (2.45 ± 0.446, $p = 0.078$) conditions however did not meet the significance threshold, unlike the directional analysis.

No statistically significant differences were found between either the dominant or non-dominant legs' single maximum landing force.

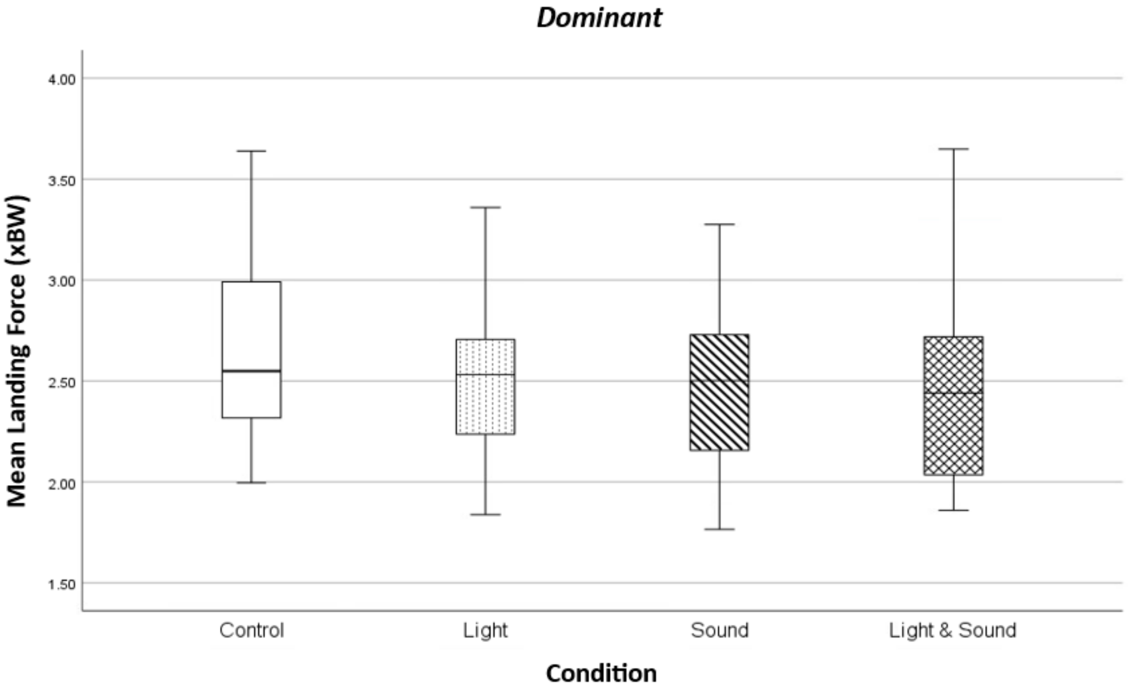


Figure 4.5.2: Box plot of mean landing force expressed as a multiple of participant bodyweight Dominant leg during the four conditions (n =24).

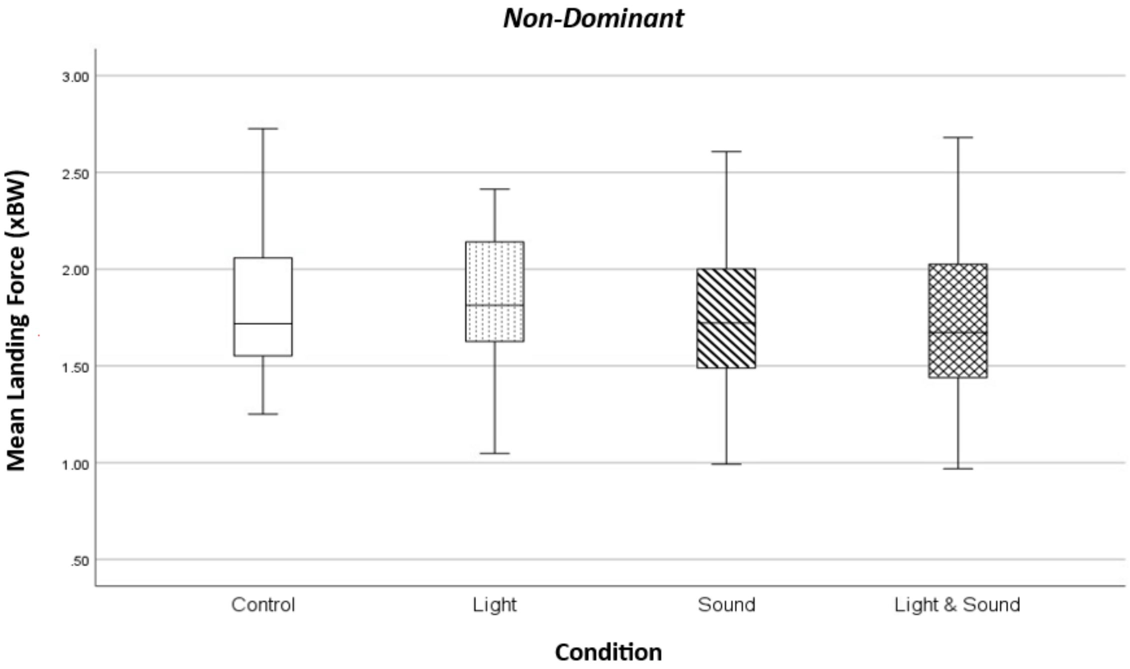


Figure 4.5.3: Box plot of mean landing force expressed as a multiple of participant bodyweight for participants' Non-Dominant leg during the four conditions (n =24).

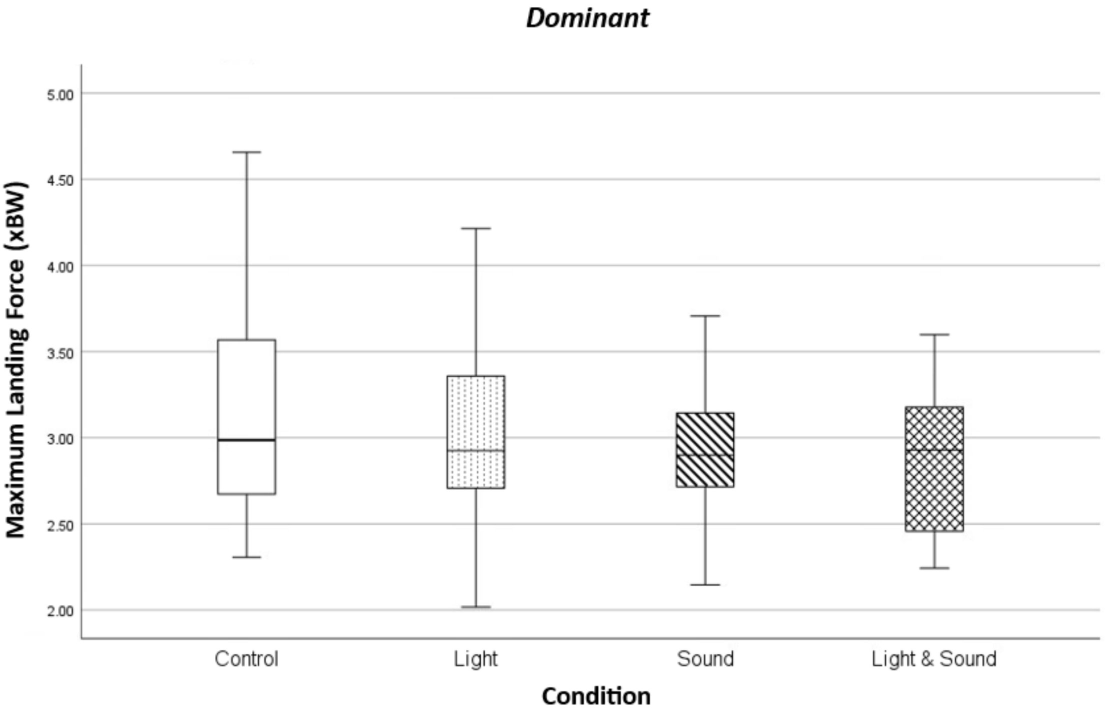


Figure 4.5.4: Box plot of maximum landing force expressed as a multiple of participant bodyweight

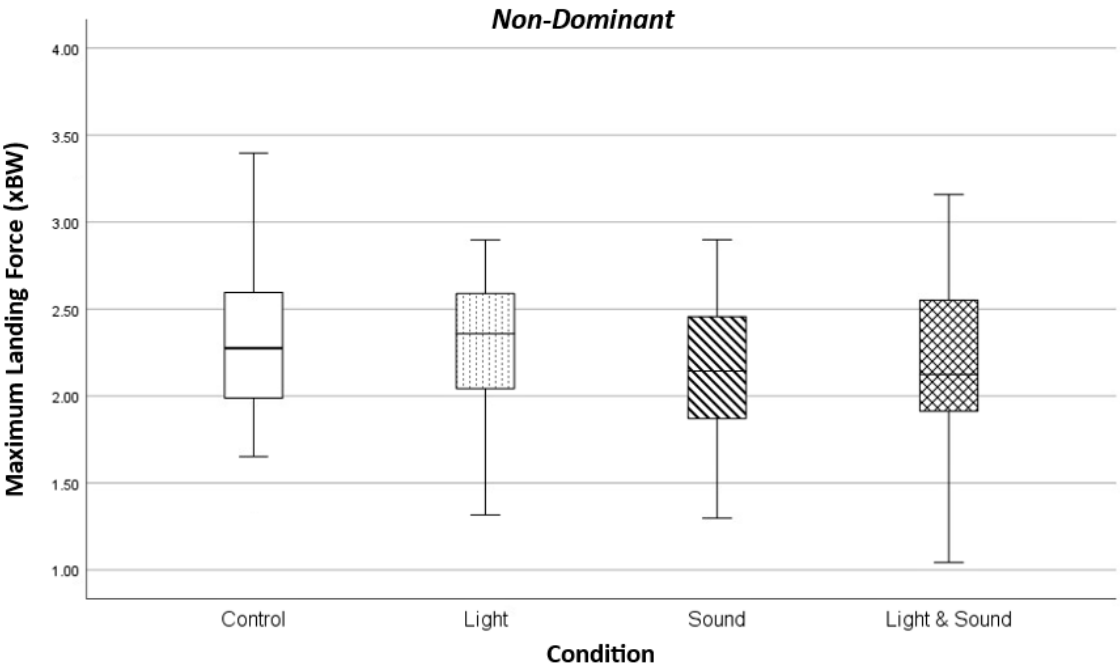


Figure 4.5.5: Box plot of maximum landing force expressed as a multiple of participant bodyweight

Table 4.5: Mean Peak Ground Reaction Force relative to bodyweight ± SD in relation to the Condition and leg measured among Male and Female Participants (n = 30). Dominant leg defined as which experienced greater vertical ground reaction force. *p value indicates the difference between Correct and Incorrect attempts. Asterisks indicate the significant differences between the conditions (* $p < 0.05$)*

Condition	***Leg***	***Peak Ground Reaction Force (xBW)***	***Leg***	***Peak Ground Reaction Force (xBW)***
Control	*Right **	*2.50 ± 0.526 **	*Dominant*	2.64 ± 0.441
	Left	*2.01 ± 0.542*	*Non-Dominant*	1.87 ± 0.457
Light	*Right*	*2.37 ± 0.435*	*Dominant*	2.50 ± 0.348
	Left	*1.99 ± 0.347*	*Non-Dominant*	1.88 ± 0.323
Sound	*Right*	*2.31 ± 0.461*	*Dominant*	2.44 ± 0.380
	Left	*1.89 ± 0.392*	*Non-Dominant*	1.77 ± 0.406
Light & Sound	*Right **	*2.32 ± 0.558 **	*Dominant*	2.45 ± 0.445
	Left	*1.91 ± 0.435*	*Non-Dominant*	1.77 ± 0.429

5. Discussion

To the best of the author’s knowledge, this is the first study with the aim of investigating the effect of differing stimulus types on landing mechanics and the first dual-tasking study to include auditory stimuli in its study methods. This study continued the trends in previous literature that the inclusion of cognitive-motor dual-tasking alters landing biomechanics although unlike previous research participants were found to land in a manner with a potential to reduce injury risk, rather than increase it, during the dual-task scenarios. However, comparisons to previous research are also difficult, as to the author's knowledge no other study involving either landing or cutting mechanics has investigated differing stimulus types so further research is required before conclusions can be made as to the effect differing stimulus presentation mediums alterations on landing mechanics and motor tasks as a whole (Giesche et al., 2021).

5.1 Time to Pass

The simulated sporting reaction time of time to pass (TTP) was found to be significantly higher in both the Light and the Sound conditions from the pre-planned control condition. The Sound condition also took participants longer to pass the ball, in both Light and Light & Sound conditions. This suggests that participants found the Sound condition the most cognitively challenging of all the conditions, which may also be inferred by it being the only condition in which participants passed in the wrong direction. The increase in TTP in both the Light and the Sound condition but not the Light and Sound combination may also indicate that the simultaneous presentation of both stimuli was less cognitively challenging than being presented with just a singular sensory input.

The increase in TTP between the Light and the Sound condition is despite research indicating choice reaction time (RT tests in which the participants must choose a response as seen in this study) is higher for Visual Stimuli rather than Auditory (Green & Gierke, 1984). This increase in TTP in our study may be due to the difficulty of identifying the correct passing direction during the Sound condition as evidenced by it being the only condition in which participants incurred errors in determining which direction to pass.

There was a statistically significant decrease in participants' TTP during incorrect attempts (930 ± 578ms) as compared to correct attempts (903 ± 485ms). This continues the trends seen within choice reaction time studies which also found unsuccessful attempts increased participants' reaction time (Rizzi, 2011). Although outside the aims of this study this difference in reaction time may warrant further investigation with previous dual-tasking studies showing lower cognition skills lead to an increase in ACL injury risk factors so there may be a link between the difficulty/success rate of a task and its effect on landing mechanics. There may be potential that this increased reaction time takes up an increased cognitive load and therefore reduces the motor control aspect during dual-tasking scenarios and may warrant further investigation around the effect of difficulty during dual-tasking scenarios.

5.2 Peak Knee Valgus Angle

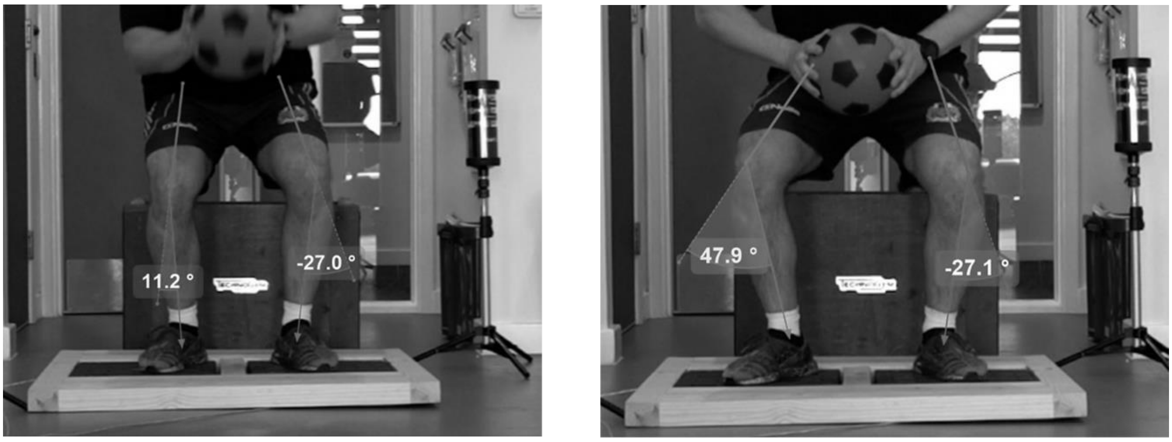


Figure 5.2.1: Example of landings observed during the Control and Light & Sound conditions: *Left: Control condition, Right: Light & Sound condition showing the more varus landing position males landed in.*

Shown in Figure 5.2.1 are examples of the observed changes in peak knee valgus angle observed between the Control and Light & Sound conditions. Participants' right legs experienced a statistically significant increase in knee valgus angle placing participants' knee alignment into a more varus landing position. Participants' right leg peak knee angle increased from 8.51 ± 14.0 degrees to 12.5 ± 16.0 degrees.

The increase to a more varus knee position is typically associated with safer landing mechanics and decreased risk of ACL injury. The findings that the right leg landed with greater knee varus is contrary to previous research which indicated that participants' dominant leg (as determined by which one experienced the higher vertical ground reaction forces), which for the majority will be the right, typically experiences greater knee valgus leading to a riskier landing strategy (Ford, Myer and Hewett, 2003).

The increase to a safer, more knee varus position may have been skewed by the 2:1 ratio of males to females in the study. When analysed as separate groups the males came close to replicating the increase in peak knee valgus angle (p = 0.054), indicating a more varus landing technique, seen between the Control and Light & Sound conditions when analysed as a collective. However, the female peak knee valgus angle was not close to significance either neither increasing nor decreasing, further indicating the differences between the sexes' landing mechanics, with females landing on average closer to neutral alignment. The study did not meet the required statistical power to make comparisons between the two sexes and therefore the different responses to dual-tasking conditions for each sex warrant further investigation.

5.3 Ground Reaction Force

The Light & Sound condition showed a statistically significant decrease in right leg pGRF. During the Control condition, participants' right leg experienced average forces of 2.5x their body weight which decreased to 2.32x their body weight during the Light & Sound condition. The decrease from the Control to the Light & Sound was also near statistical significance (p = 0.054) when assessing participants' single maximum landing force during a trial, at 3.03xBW and 2.78xBW respectively.

The decrease in pGRF during the Light & Sound condition was uncommon among previous research around dual-tasking, with at least 6 studies in Table 1.4 seeing increases in landing forces for dual-tasking conditions when compared to the control (Almonroeder et al., 2018; Dai et al., 2018; Herman et al., 2016; Imai et al., 2022; Kajiwara et al., 2022; Shinya et al., 2011). The decrease may be explained by alterations in lower limb joint mechanics due to the increased demand due to dual-tasking. Breakdowns in exercise form and quality have already been shown by Schnittjer et al., (2020) with dual-tasking decreasing the movement quality of tuck jumps when performing either easy or difficult digit recall activities simultaneously with the jumps.

When assessed as either the dominant or non-dominant leg, the dominant leg approached a statistically significant decrease in pGRF during both the Sound and Light & Sound conditions ($p = 0.072$, $p = 0.078$), however did not meet the relevant thresholds. This discrepancy in significant differences only when assessing the limbs directionally may be explained by the region in which proprioceptive tasks take place within the brain. Proprioceptive tasks take place predominantly within the right hemisphere of the brain and have been linked to decreased motor control in the right leg when participants prefer to use their right leg as their kicking leg in soccer (Strong et al., 2023). Although the dominant kicking leg wasn’t determined within the trial, 83% of participants absorbed more force on average in their right leg, however, the kicking leg may not always be the leg capable of producing more force (Vaisman et al., 2017). This decrease in motor control may be among one of the reasons participants experienced statistically significant decreases in the right leg pGRF and not when assessed as either dominant or non-dominant legs. This was also linked further with the earlier discussed pKVA increases also occurring in the right leg. Further investigation is required into brain activity and its function in lower limb kinematics as well as the potential interference of differing stimulus types on cognitive motor skills during dual-tasking scenarios.

5.4 Peak Knee Flexion Angle

Participants experienced no statistically significant changes in peak Knee Flexion Angle during any of the four conditions. This was consistent with the previous research in which the two previous studies that measured peak Knee Flexion Angle during landing also found no statistically significant differences when comparing single and dual-task landing scenarios. Both previous dual-tasking studies did however find statistically significant differences in initial Knee Flexion Angle however this was not measured within this study (Dai et al ,2018; Mache et al, 2013).

Peak Knee Flexion angle was chosen to be measured to test whether participants performed a technique known as a “soft landing” during the stimulus conditions as compared to the control. A soft landing is a landing technique in which athletes will try to decrease the total landing force they absorb through the alteration of their landing mechanics; this is primarily achieved by increasing knee and ankle flexion angles (Tamura, Akasaka and Otsudo, 2021; Wernli et al., 2016).

Although not statistically significant, participants did see a decrease of roughly 3° during the dual-task conditions as compared to the Control. This is in addition to the decreased pGRF seen in the right leg between the Control and Light & Sound conditions and near statistically significant decreases in dominant leg landing force from the Control to the Sound and Light & Sound conditions. This combination of a decrease in landing force and potential decrease in peak Knee Flexion Angle may indicate, whether consciously or not, participants ended up landing with safer kinematics and kinetics in regard to ACL injury risk.

Interestingly, there seems to be no relationship between TTP and the potential that a participant was performing a soft landing. It may be expected that an increase in TTP in during dual-task conditions is caused in part by participants performing a softer landing technique, which requires them to perform a deeper squatting motion and then rise to a more upright position before passing the ball, which takes a longer amount of time. TTP however, was found to not be significantly different between the Control and the Light & Sound conditions, which saw a statistically significant decrease in Right Leg landing force which indicates a softer landing, unlike the Light and the Sound conditions which both differed from the control in TTP but did not see a statistically significant decrease in either landing force or knee flexion angle. In addition, during the Sound condition, participants took significantly longer to pass the ball from all other conditions including Light & Sound however it was the Sound condition which was found to have the most similar results to the Light & Sound condition in terms of landing force when measured both as separate directionally (r(22) = 0.844, p=0.001) or as dominant/non-dominant limbs (r(22) =0.681, p = 0.001). In summary, this may indicate that any changes in the TTP during different conditions were not due to changes in participants performing a softer landing and therefore taking longer to get into a passing position but instead more likely caused by an increase in the cognitive demands of a task requiring participants to take longer to process the presented stimuli before being able to make their pass. This may have practical implications for future investigations into dual-tasking as a training or rehabilitation method in which the difficulty of the task may affect the cognitive aspect of the training more than the motor aspect, however much more research is required before such conclusions can be determined.

5.5 Limitations

This study has several limitations to address, as earlier discussed there was an uneven number of males and females recruited. Males and females are known to have both different landing mechanics and choice reaction time values when responding to visual and auditory stimuli. Further research is essential to developing our understanding of dual-tasking’s effect on landing mechanics and the effect of differing stimulus types with either single-sex studies or significantly powered studies to make comparisons (Jain et al., 2015; Butler et al., 2013)

Additionally, the kinematics and kinetics measured would have ideally been measured using a synchronous 3D motion capture and force plate system to investigate multiple joint sites, such as the hip and ankle, as well as calculating joint moments during the different trials. Although 2D motion capture has been shown to be close to 3D motion capture accuracy in some measurements, including frontal plane projection angle, it was not available within the confines of this study. 3D motion capture is considered the gold standard for assessing frontal and sagittal plane joint angles and if available would have increased both the accuracy and scope of the study (Peebles, Arena and Queen, 2021; Sorenson et al., 2015)

Finally, greater statistical strength could have been achieved without the loss/inability to record certain variables such as TTP and pGRF for 6 of the participants. This inability to record these variables came largely due to technical malfunctions from the equipment but could have increased the strength of the study.

5.6 Further Research

As discussed throughout, this study is one of the first to investigate the effect of differing stimulus types on landing mechanics and injury risk factors. An increased body of literature is needed within a variety of subject areas surrounding both auditory stimuli on their own and how they differ from the more understood visual stimuli effect in both landing mechanics and cutting tasks during dual-tasking scenarios.

Of the relevant research that should follow, the interaction between auditory stimuli when present in higher-order cognitive tasks should be investigated. Dai et al (2018) and Schnittjer et al (2020) both found no significant alterations in landing mechanics when investigating the differences between easy and difficult cognitive tasks when presented visually, yet the interaction between auditory stimuli remains unknown in higher-order tasks.

Additionally, both levels of cognition and level of neuromuscular control may affect an athlete's risk of landing injury. Lapointe et al (2018) and Herman et al (2016) found that participants with either a concussion or lower cognitive skills showed an increased risk of ACL injury when under dual-tasking scenarios. Kipp et al (2013) also found that the increase in risky landing mechanics decreases for those with experience in landing sports, suggesting that increased levels of neuromuscular control within a movement task may reduce the risk of injury, potentially due to a decrease in the brain capacity needed for such movements. This may be linked to higher-order cognitive tasks and the effect that limited capacity theory may play within both the mental and physical aspects of dual-tasking scenarios (Buschman et al., 2011).

6. Conclusion

To conclude, participants experienced alterations in lower extremity landing mechanics, with an increase in knee valgus angle and a decrease in peak ground reaction force, when presented with simultaneous visual and auditory stimuli during dual-tasks mimicking scenarios seen in Netball or Basketball. Although these alterations in were not related to an increased risk of ACL injury with decreases in landing force and greater knee valgus angle, these findings expand on the growing but still underdeveloped body of literature investigating the relationship between dual-tasking scenarios and their potential increase on injury risk. Furthermore, the relationship between practical performance within sporting tasks and different stimulus types was investigated, with auditory stimuli decreasing both the reaction time and accuracy of participants' sporting tasks when compared to either the control or any trial involving visual stimuli. The findings of how participants took the most amount of time to identify which direction to pass when only presented with an auditory stimulus may inform future practical implications for how ball sport practitioners communicate with one another and train. It may be beneficial for participants to be given stimuli from both an auditory and visual source when returning to training following injury, especially ACL, as this study demonstrated that there were found to be reduced risk factors when doing so.

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Appendices

Consent Form

Study Title: The Effects of Cognitive Dual Tasking on Landing Mechanics

Before you consent to participating in the above study we ask that you read the participant information sheet and mark each box below with your initials if you agree. If you have any questions of queries please speak to the researcher before signing the consent form.

1. ☐ I confirm that I have read the information sheet and understand what is expected of me within this study.

2. ☐ I confirm that I have had the opportunity to ask any questions and that they have been answered.

3. ☐ I understand that I am voluntarily taking part in this study and can withdraw at any time without giving any reason.

4. ☐ I understand that my data will be made anonymous and may be published. The necessary steps will be taken to protect the anonymity of participants involved in this project.

5. ☐ I understand that once my data has been made anonymous it may not be possible for it to be withdrawn, though every attempt will be made to extract my data up to the point of publication.

6. ☐ I understand that the researcher will discuss data with their supervisor as needed.

7. ☐ I consent to Lancaster University keeping the data collected for 10 years after the completion of this study.

8. ☐ I consent to take part in the above study.

Name of Participant: **Signature:** **Date:**

Name of Researcher: **Signature:** **Date:**

Participant Information Sheet

Title of Study: **The Effects of Cognitive Dual Tasking on Landing Mechanics**

Name of Researcher(s): Luke Scott
Dr Theo Bampouras

My name is Luke Scott and I am conducting this research project as a student in the MSc by Research in Medical Science programme at Lancaster University, Lancaster, United Kingdom.

What is the purpose of the study?

The study aims to investigate the relationship between multi-tasking and risk of injury in sporting scenarios.

Why have I been invited?

You have been approached as the study requires people between the ages of 18-35 that are injury free.

Inclusion criteria:

- Male or Female between 18-35 years old
- Deemed recreationally active (at least 150 minutes of moderate activity per week)

Exclusion criteria:

- Currently having or history of lower limb injuries which could be aggravated during jumping activities

What will I be asked to do if I take part?

If you decide to take part in the study you will be asked to complete a consent form and questionnaire to determine your age, level of physical activity and details of any current/previous lower limb injuries.

During the session following a brief warm up you will be asked to complete repetitions of sub-maximal broad jumps under 5 separate conditions. These conditions will be; standard broad jump, pre-planned pass, responding to an auditory stimulus, responding to a visual stimulus and responding to a combined visual and auditory stimulus.

Will my data be kept confidential?

The data collected for this study will be stored securely and only the researchers conducting this study will have access to this data, however authorised regulators are also legally allowed to check that the study is being carried out correctly.

All information that is collected about you during the study will be kept strictly confidential. Hard copies of information will be kept securely within a locked cabinet and all files on a computer will be encrypted and anonymised.
The data will be merged (e.g. averaged) and used for writing up my Thesis and may lead to a publication, in part or whole. No individual will be identified in the Thesis or any of the publications.

Are there any risks?
There is a very small risk of a minor lower limb injury during landing, however this is not outside the risk you have when playing sport. However, if you experience any distress following participation you are encouraged to inform the researcher and contact the resources provided at the end of this sheet.

Are there any benefits to taking part?
Although you may find participating interesting, there are no direct benefits in taking part.

What if you no longer wish to carry on with the study?
Your participation is entirely voluntary and you may withdraw at any time from the study without having to give a reason or disadvantage to you.

What will happen to the results of the study?
The results of the study will be summarised and reported into a Masters thesis for a MSc by Research in Medical Sciences and may be presented at a conference or submitted for publication in an academic or professional journal.

Who has reviewed the study?
This study has been reviewed and approved by the Faculty of Health and Medicine Research Ethics Committee at Lancaster University. If you have any questions, please contact a member of the study team.

Where can I obtain further information about the study if I need it?
If you require any additional information about any of the details regarding the study, please contact:
Luke Scott, l.scott7@lancaster.ac.uk, Main researcher
Dr Theo Bampouras, t.bampouras@lancaster.ac.uk, Supervisor

Health & Medicine | Lancaster University

Complaints
If you wish to make a complaint or raise concerns about any aspect of this study and do not want to speak to the researcher, you can contact:

Dr Bob Lauder, Director of Sports Science
r.lauder@lancaster.ac.uk
Lancaster University
Lancaster
LA1 4YG

If you wish to speak to someone outside of the study, you may also contact:

Dr Laura Machin Tel: +44 (0)1524 594973
Chair of FHM REC Email: l.machin@lancaster.ac.uk
Faculty of Health and Medicine
(Lancaster Medical School)
Lancaster University
Lancaster
LA1 4YG

Thank you for taking the time to read this information sheet.

MED.311 Biomechanics III – Risk Assessment

Participant’s full name:

Emergency contact number:

This form needs to be completed and returned to the relevant member of staff before participating in any scheduled physical activity or testing related to this module.
An indicative (but not exhaustive) list of activities that you are likely to participate in / be tested on can be found below. If you are unsure about any of these, or any of the activities you will perform, please ask your tester for more information.

Walking
Running
Jumping
Cycling
Hopping
Weight lifting
Physical conditioning exercises
Stretching

An indicative (but not exhaustive) list of conditions that could prevent you from partaking are:

Experiencing chest pains after exercise
Getting out of breath at rest or slight exertion
Often getting headaches, dizziness, or fainting spells
Having been diagnosed with a heart condition
Regularly taking drugs or medicines
Having pain or limited movement in any joints
Pregnancy

If you have any of these conditions, others not mentioned above that would stop you from participating or you have concerns about your ability to take part in any of the activities, you may need additional support; please ask the module tutor for advice.

Are you able to participate in physical, exercise and sporting activities? ***Yes*** ***No***

If you answered ‘No’ to the above question, you may need additional support; please ask the module tutor for advice.

The information given above is to the best of my knowledge a true and accurate record. I understand that I need to notify staff of any changes in my circumstances. I consent to take part in the study’s activities at my own risk, and, if necessary, will have obtained GP clearance to do so.

Signed (participant): Date:

Signed (Witness): Date:

CONSORT 2010 checklist of information to include when reporting a randomised trial*

Section/Topic	Item No	Checklist item	Reported on page No
Title and abstract			
	1a	Identification as a randomised trial in the title	1
	1b	Structured summary of trial design, methods, results, and conclusions (for specific guidance see CONSORT for abstracts)	2
Introduction			
Background and objectives	2a	Scientific background and explanation of rationale	9
	2b	Specific objectives or hypotheses	32
Methods			
Trial design	3a	Description of trial design (such as parallel, factorial) including allocation ratio	33
	3b	Important changes to methods after trial commencement (such as eligibility criteria), with reasons	33
Participants	4a	Eligibility criteria for participants	33
	4b	Settings and locations where the data were collected	35
Interventions	5	The interventions for each group with sufficient details to allow replication, including how and when they were actually administered	36
Outcomes	6a	Completely defined pre-specified primary and secondary outcome measures, including how and when they were assessed	38
	6b	Any changes to trial outcomes after the trial commenced, with reasons	33
Sample size	7a	How sample size was determined	41
	7b	When applicable, explanation of any interim analyses and stopping guidelines	
Randomisation:			
Sequence generation	8a	Method used to generate the random allocation sequence	37
	8b	Type of randomisation; details of any restriction (such as blocking and block size)	37
Allocation concealment mechanism	9	Mechanism used to implement the random allocation sequence (such as sequentially numbered containers), describing any steps taken to conceal the sequence until interventions were assigned	
Implementation	10	Who generated the random allocation sequence, who enrolled participants, and who assigned participants to interventions	

Blinding	11a	If done, who was blinded after assignment to interventions (for example, participants, care providers, those assessing outcomes) and how	
	11b	If relevant, description of the similarity of interventions	
Statistical methods	12a	Statistical methods used to compare groups for primary and secondary outcomes	41
	12b	Methods for additional analyses, such as subgroup analyses and adjusted analyses	41
Participant flow (a diagram is strongly recommended)	13a	For each group, the numbers of participants who were randomly assigned, received intended treatment, and were analysed for the primary outcome	42
	13b	For each group, losses and exclusions after randomisation, together with reasons	33
Recruitment	14a	Dates defining the periods of recruitment and follow-up	
	14b	Why the trial ended or was stopped	
Baseline data	15	A table showing baseline demographic and clinical characteristics for each group	33
Numbers analysed	16	For each group, number of participants (denominator) included in each analysis and whether the analysis was by original assigned groups	33
Outcomes and estimation	17a	For each primary and secondary outcome, results for each group, and the estimated effect size and its precision (such as 95% confidence interval)	42
	17b	For binary outcomes, presentation of both absolute and relative effect sizes is recommended	
Ancillary analyses	18	Results of any other analyses performed, including subgroup analyses and adjusted analyses, distinguishing pre-specified from exploratory	42
Harms	19	All important harms or unintended effects in each group (for specific guidance see CONSORT for harms)	
Limitations	20	Trial limitations, addressing sources of potential bias, imprecision, and, if relevant, multiplicity of analyses	61
Generalisability	21	Generalisability (external validity, applicability) of the trial findings	55
Interpretation	22	Interpretation consistent with results, balancing benefits and harms, and considering other relevant evidence	55
Other information			
Registration	23	Registration number and name of trial registry	
Protocol	24	Where the full trial protocol can be accessed, if available	
Funding	25	Sources of funding and other support (such as supply of drugs), role of funders	

Citation: Schulz KF, Altman DG, Moher D, for the CONSORT Group. CONSORT 2010 Statement: updated guidelines for reporting parallel group randomised trials. BMC Medicine. 2010;8:18.