UNIVERSITY OF
DERBY

Incorporating End-User Feedback in the Development and Validation of a Smart Textile for assessing Sports Training and Performance

By

Nathan James Toon

Programme of Study:

Master of Philosophy (MPhil)

Submitted:

March 2023

Declaration

I declare that:

a) All work described in this report has been carried out by me, and all the results (including survey findings, etc) given herein were first obtained by me, except where I may have given due acknowledgement to others.

b) All the prose in this report has been written by me in my own words, except where I may have given due acknowledgement to others and used quotation marks, and except for also occasional brief phrases of no special significance which may have been taken from other people's work without such acknowledgement and use of quotation marks.

c) All the figures and diagrams in this report have been devised and produced by me, except where I may have due acknowledgement to others.

I understand that if I have not complied with the above statement, I may be deemed to have failed the project assessment and/or I may have some other penalty imposed upon me by the Board of Examiners.

Signed: [redacted] **Date: 19/06/2023**

Name: Nathan James Toon

Programme: Master of Philosophy (MPhil)

Abstract

Objectives: The aims of the research project were to explore the need and desire of a new sport wearable within applied practice by creating dialogue with the end-users. Furthermore, the research project sets out to quantify the reliability and validity a new sports wearable, KiTT (Knitted intelligent Textile Tracker), against the current gold-standard three-dimensional motion-analysis counter-part.

Methods: Study 1 will utilise semi-structured interviews to create dialogue between the researcher and end-users. This will help provide an image into the current use of technology within applied practice. Furthermore, study 2 will capture and calculate the relative knee angles from KiTT's raw resistance, and compare the results to that of Vicon, where reliability and validity will be assessed; this is imperative before task-specific research.

Results: Study 1 identified a need, and requirement for new sport wearables, specifically in the form of e-textiles. This would enable end-users to adopt technology into their work, potentially enhancing their output. In addition, study 2 suggests that KiTT serves as a valid and reliable tool at recording relative knee angle across five commonly used sporting exercises, with high degrees of accuracy.

Conclusion: End-users stated a need and requirement for technology such as KiTT to be created for adoption within their practice. Current systems are often inaccessible and can lead to performance losses. KiTT serves as a valid alternative to motion-capture, whilst offering more benefits to the user (cost-friendly, easy to use, and portable). When investigating an individual's relative knee angle, KiTT should be considered especially in specific testing conditions.

Key Words:

Validation, Sport, Wearables, E-Textiles, Motion-Capture

Acknowledgements

I would like to thank my supervisory team, Dr Ruth Ashton, Dr Mark Faghy, and Simon McMaster, and all members of staff at Footfalls and Heartbeats (Ltd) for their continuous support throughout the past 18 months, as well as the ERDF for the funding of the research project. I would like to thank my friends and family for always pushing me to be the best version of myself, and making sure I keep going when times are tough. Finally, I would like to give the greatest of thanks to my amazing wife, Rebecca Owen-Toon for sticking with me through the highs and lows, it would not have been possible without you.

Table of Contents

List of Tables

List of Figures

Abbreviations

.csv – Comma Separated Values

3D – Three-Dimensional

ANK – Lateral Malleoli

ASIS – Anterior Superior Iliac Spine

BD – Box Drop

CMJ – Countermovement Jump

ECG - Electrocardiogram

EMS – Electrical Muscle Stimulation

FG – Focus Group

GPS – Global Positioning Systems

HEE – Base of the Calcaneus

HR – Heart Rate

IMU – Inertial Measurement Unit

KiTT – Knitted Intelligent Textile Tracker

KNE – Lateral Epicondyle of the Tibia

LC – Leg Curl

LoA – Limits of Agreement

MRI – Magnetic Resonance Imaging

PSIS – Posterior Superior Iliac Spine

RKA – Relative Knee Angle

RMSE – Root Mean Square Error

SI – Structured Interview

SJ – Squat Jump

SSI – Semi-Structured Interview

STA – Soft Tissue Artefact

TOE – Base of the 2nd Metatarsal

UI – Unstructured Interview

VAR – Video Assistant Referee

VO_2 max – Maximal Aerobic Capacity

WBS – Weighted Back Squat

Chapter 1: Project Introduction

Smart textiles are an evolving piece of technology, which are relatively new and untouched by the applied practitioners (Meena et al., 2023). Smart textiles offer the user a new form of data collection, where the participant can wear a purpose-built garment that replaces a sock, a knee sleeve, an elbow sleeve, or undershirt which traditionally do not collect data (Adesida et al., 2019; Meena et al., 2023; Semjonova et al., 2022). One smart textile that has been developed to measure lower-limb kinematics is the Knitted intelligent Textile Tracker (KiTT), created by Footfalls and Heartbeats (UK) Limited (*Nottingham, UK*).

Research into KiTT has been on-going since its inception, with collaboration taking place at the University of Derby since 2021. The current research project serves as a development and continuation from the 2021 research project, where KiTT was assessed for validity within a resistance-trained population (Toon et al., 2022). The current development stage of KiTT requires additional testing to quantify the degree of reliability and validity, before assessing its accuracy, and ultimately entering the market for use.

Furthermore, the current research project was established to assess the current application of technology within applied sports practice, and what end-users and coaches desire and require from their technology. To understand the views of end-users and coaches, semi-structured interviews will be conducted focussing on four key areas. These areas will provide an insight into how coaches currently operate, how their technology is utilised (if applicable), and what they would deem necessary from new pieces of technology to aid their work. The current research aims to aid coaches by providing a technological solution that offers both reliable and valid data, as well as being easy-to-use, and time-efficient (Halson, 2014). Following guidance from Wilson et al. (2017), an interview schedule was devised to collect qualitative data from the sample, which would later inform future research into an evolving e-textile. KiTT, which will be validated within the research project has the potential to capture several lower limb kinematic variables. KiTT incorporates a textile strain sensor, where an electronics module within the sleeve measures a change in voltage which is experienced through motion (Brendgen et al., 2022). Through post-collection software, the kinematic variables from KiTT can be extracted and translated into metrics which can be compared directly to the gold-standard equipment. Following on from the results and guidance from chapter 3, KiTT's reliability and validity will be investigated to determine whether the technology can be offered as a replacement to current technological solutions and works as intended. To assess the reliability and validity of KiTT, several sporting exercises will be completed amongst a sample, with a 3D motion-capture system acting as the gold-standard reference (Tanner et al., 2015; van der Kruk & Reijne, 2018). With all new sport technology, there needs to be a period of reliability and validity assessment to ensure the results are as expected (Tanner et al., 2015).

Chapter 2: Literature Review

2.1 Technology in Sport

2.1.1 Origins and Current Application of Technology

Sport has been played for hundreds of years across the world, where until the 20th century, participants relied on just skill, passion, and desire to excel. However, in the late 19th, and 20th century, there were some early forms of technology in use, such as the photo finish (1888), physiological testing equipment (1920's), a screen to display instant replays (1955), and electronic timing pads that were used within swimming (1957) (Omoregie, 2016). Towards the late 20th century, technology in sport became more common, with paralympic athletes making use of lower limb prosthesis' in 1988, and serve-speed becoming more available in tennis, in 1991 (Dyer, 2015).

The adoption of technology within sport has increased drastically since the turn of the 21st century (Mali & Kumar Dey, 2020). Utilising technology can be defined within six distinct categories: self-technology, landscape, implement, rehabilitative, movement, and database; emphasising the wide-range of applications possible (Omoregie, 2016). Self-technology is concerned with improving the individual, which contains performance enhancing drugs and supplements, as well as prosthesis/bionic limbs, and psychological interventions (Marks & Michael, 2001; Omoregie, 2016; Reyes-Bossio et al., 2022). Landscape technology is concerned with utilising the environment around the sport, to either benefit performance or the spectator's view on the event (Omoregie, 2016). Examples of landscape technology are 'JumboTron' screens, and global position system (GPS), where satellites are used to triangulate an individual’s position on the field, and collect multiple variables related to performance (Omoregie, 2016; Theodoropoulos et al., 2020; Yunwei & Shiwei, 2019). Implement technology is integrated directly into performance, and is there to aid competition, in the form of shark suits (swimming), high-tech running shoes, and advances tennis rackets and golf clubs (Bermon et al., 2021; Lees, 2019; Morales et al., 2019; Omoregie, 2016). Rehabilitative technologies are concerned with the overall health and well-being of the participant. These technologies aim to either resolve an on-going injury, regardless of the severity, or to help avoid an injury through preventative measures (Omoregie, 2016; Patterson et al., 2008). Whirlpools, electronic muscle stimulation (EMS), and clinical diagnostic equipment, are all examples of rehabilitative technologies with the same objective of bringing the user back to full health (Finnoff et al., 2016; Patterson et al., 2008; Pinar et al., 2012). Movement analysis is another term for performance analysis, where the performance is recorded in either training or competition, and later reviewed to better understand and learn how to beat an opponent or improve a personal performance (Gomez-Ruano et al., 2020; Mackenzie & Cushion, 2012; Omoregie, 2016). Finally, database technologies are largely concerned with the analysis and storage of data collected (Omoregie, 2016).

Within sport and exercise, technology is widely used to collect data, monitor individual’s progressions (e.g., jump height, power, speed), workloads, and performance, as well as to ensure correct decisions are given within game situations (Gathercole et al., 2015; Muniz-Pardos et al., 2019; Singh Bal & Dureja, 2012). Conventional technological systems such as motion-capture and force plates allow the user to collect accurate and valid data, with high levels of accuracy (Beckham et al., 2014; Gathercole et al., 2015). Although these methods have a high level of sensitivity and accuracy, they are hindered by a lack of practicality in sporting situations, with athletes and coaches requiring access to testing, and objective data in a timely and efficient manner. As a result, technological advancements are being developed to aid coaches and practitioners within sports settings, to address their specific needs and demands (Adesida et al., 2019; Luczak et al., 2019). Contemporary methods, including sport wearables, often relay data to coaches and practitioners instantaneously in real-time, providing numerous benefits such as the live monitoring of an individual's workload and intensity, which can positively impact a team performance, as well as reducing injury risk of the user (Luczak et al., 2019). Access to real-time data allows coaches and practitioners to instantly tailor training plans for their athletes, depending on their level of exertion and their response to a stimulus. This can be useful as the risk of injury and effects of fatigue may increase if an athlete is working too hard, whilst ensuring athletes are not coasting through sessions, and not working as hard as they could (Adesida et al., 2019; Seshadri et al., 2019; Seshadri et al., 2021).

2.1.2 Current Use of Technology

The increase in technological adoption is giving coaches and practitioners more data than ever before (Cabarkapa et al., 2022; Nguyen et al., 2015; Svilar et al., 2019). The vast amount of data available to coaches can aid the formulation and deployment of relevant, individualised specific training plans to their athletes, based on data (Svilar et al., 2019). Certain technological systems require the athlete to remain in one specific area when performing motion, which does not necessarily translate to how an individual moves during sporting performance (Cabarkapa et al., 2022). These methods are often set as the gold-standard, and provide the user with accurate valid data, however, are not regarded as the most optimal method when collecting dynamic/sport-specific data (Nguyen et al., 2015; van der Kruk & Reijne, 2018). More portable and accessible devices such as inertial measurement units (IMU's), provide coaches with accurate data following an appropriate calibration process (Roell et al., 2019). However, as a result of technological advancements within IMU's, the calibration process is not necessary in all cases, due to the calibration process occurring during the manufacturing steps (Zhou et al., 2020). Eliminating the calibration process allows end-users to collect data at a faster rate, allowing for a greater amount of data to be collected.

Within sport, referee's and officials are largely responsible for ensuring a fair game is carried out, and the rules are properly adhered to, however this is not always possible (Firek et al., 2020). To help relieve some of the pressure from the officials, systems have been developed to increase accuracy of decisions, and reduce the likelihood of errors within the game (Collins & Evans, 2012; Firek et al., 2020). Within tennis and cricket, hawk-eye has been developed and implemented to aid the umpire with close decisions, as to whether the tennis ball has landed within the court boundaries, or if the cricket ball would be hitting the wicket had it not hit the batter's leg (Bal & Dureja, 2012; Collins & Evans, 2012; Omoregie, 2016). These systems have been in-place for numerous years and have gone through rigorous testing procedures to allow for maximum accuracy (Bal & Dureja, 2012; Omoregie, 2016). More recently in football, the video assistant referee (VAR) has been implemented to give referee's more time and viewpoints of situations within competition (Holder et al., 2022). VAR helps with decisions such as awarding penalties, offside calls, and red-card situations (Holder et al., 2022; Samuel et al., 2020). However, VAR, unlike hawk-eye, requires human input and judgement in certain stations (i.e., penalty, and red card decisions), and therefore often comes under mass amounts of scrutiny (Holder et al., 2022; Lago-Peñas et al., 2020; Samuel et al., 2020).

Another significant use of technology is to increase performance, which can be achieved through a wide variety of means (Adesida et al., 2019). Technology can be in the form of prosthesis, swimming costumes, running shoes, training aids and equipment, to increase efficiency, reaction time, endurance, strength, and flexibility as well as much more (Dyer, 2015; Hébert-Losier & Pamment, 2023; Hutchinson, 2008; Politopoulos et al., 2015). For a paralympic athlete, a lower-limb prosthesis may allow them to participate within running events. These prosthesis' will be created and tailored to the individual and the event, to ensure performance is maximised (Bragaru et al., 2012; Dyer, 2015). For example, if an individual is competing in a short distance event (i.e., 100/200 metres), the prosthesis will be designed to provide more spring and re-coil to allow the user to achieve higher speeds (Bragaru et al., 2012; Dyer, 2015; Tacca et al., 2022). In swimming, shark suits were developed to allow the individual to move through the water faster, by reducing the surface area that is in contact with the water (Morales et al., 2019). This design was adapted and developed from previous swimsuits, which all aimed to make swimsuits tighter and more compressive without restricting the range of motion (Hutchinson, 2008; Morales et al., 2019). Another significant technological advancement is the development of running shoes, with manufacturers often patenting their inventions along with claims of increasing performance (Sun et al., 2020). Research supports the notion that specific running events require specific running shoes, with longer distance events requiring more cushioning and less responsive footwear, to that of shorter distance events (Bermon et al., 2021; Lin et al., 2022; Sun et al., 2020). As well as garments that can increase the individual's performance, there are a vast amount of training equipment which can also aid performance. Badminton players require fast reaction time, and devices such as the Batak wall and light pods can help improve this component of fitness (Ellison et al., 2017; Gierczuk & Bujak, 2014). To assess physiological variables such as heart rate (HR) and aerobic capacity (VO_2 max), there are devices that can measure these variables as well as many more, which can help prescribe and inform an individual's training (Liu et al., 2019; Scribbans et al., 2016).

Technology can also be adopted to monitor, diagnose, and help treat an injury, as well as be used for recovery (Chen, 2022; Mayne et al., 2021; Vellios et al., 2020; Zhang & Tian, 2022). X-rays can display fractures and breaks in thick, dense objects such as bones, whilst a magnetic resonance imaging (MRI) system can detect changes and abnormalities in soft-tissue, such as muscles, ligaments, and tendons (Chen et al., 2012; Crema et al., 2015). Often, once an injury is identified and properly diagnosed, treatment plans will be established and followed on the journey to recovery. If the injury is muscular, one form of treatment is EMS (Pinar et al., 2012). EMS helps increase the blood flow to the desired area, which in turn delivers more oxygen rich blood to the site whilst removing toxins and debris (Hedt et al., 2022; Pinar et al., 2012). In a schedule where there are a lot of fixtures/events in a short-time frame, recovery is key, especially in helping reduce the risk of injury (Kraemer et al., 2009). A form of technological recovery is cryotherapy. This is where individuals enter a chamber that is extremely cold for a period, exposing themselves to temperature lower than -110° (Lombardi et al., 2017). These chambers aid recovery by reducing the amount of inflammation present and any accumulation, as well as enhancing overall recovery (Bouzigon et al., 2021; Lombardi et al., 2017).

An important tool in monitoring workload of athletes is technology that relays information, which can either be viewed retrospectively, or through developments, in real-time (Seshadri et al., 2021; Van Hooren et al., 2020). More recently, coaches can instantly tailor an individual’s workload depending on the data produced by the user, which can ultimately help reduce injury prevalence of an athlete (Seshadri et al., 2019; Seshadri et al., 2021). Traditional data collection systems often require the user to collect the data, and analyse the results at a later point, whether that be immediately after collection, or hours after (van der Kruk & Reijne, 2018). The new developments in access to real-time technology often provides practitioners and coaches with additional benefits. These devices are often portable and allow for data collection to occur in a non-laboratory/controlled environment, where game settings and environments can be replicated (Woods et al., 2020). This allows athletes to move in a way that they typically would within a game situation, which increases the validity of the data that is gathered (Woods et al., 2020). Depending on the session/sport, these devices are often able to capture data in an outdoor setting, where traditional systems such as optoelectronic camera systems are unable to due to negative influence from direct sunlight affecting the sensors (Ometov et al., 2021; Seshadri et al., 2019; van der Kruk & Reijne, 2018).

2.1.3 Understanding the Use of Technology within Practice

To combat some of the issues coaches and practitioners face with current sport technology, new wearable devices have been developed (Adesida et al., 2019). Sport wearables is a rapidly growing sector with the market currently estimated at $24.57 billion, with the growth expected to continue at 24.7% annually until 2026 (Chandrasekaran et al., 2020). Wearables devices have multiple uses, with two broad and distinct categories including physiological sensors, and movement sensors (Li et al., 2016). Physiological sensors have the capacity to measure HR and temperature, as well as a combination of physiological variables and movement, whilst movement sensors have the capacity to measure step frequency, acceleration, and distance (Adesida et al., 2019; Chandrasekaran et al., 2020; Li et al., 2016). In addition to collecting data, wearables often have the capacity to store and analyse data in real-time providing the user with an all-round experience of data collection (Chandrasekaran et al., 2020; Finkelstein et al., 2016).

To collect physiological measurements, wearables such as smart watches, chest and shoulder straps, and capsules have been developed (Adesida et al., 2019; Li et al., 2016; McKenzie & Osgood, 2004; Terbizan et al., 2002). Heart rate is recorded commonly via a smart watch, with the Apple Watch Series 3 and Fitbit Charge 2 having the highest levels of agreement compared to a gold-standard reference electrocardiogram (ECG) (Auepanwiriyakul et al., 2020; Nelson & Allen, 2019). The Apple Watch Series 3 had a mean agreement of 95%, with a deviation of 1.8 beats per minute, with the Fitbit Charge 2 having a mean agreement of 91%: a deviation of 3.5 beats per minute (Nelson & Allen, 2019). Watches are more common amongst users who are operating on a budget, or are just getting into fitness, with more advanced users usually opting for chest straps to measure HR. According to research conducted by Pasadyn et al. (2019), the Polar H7 chest strap has the greatest degree of agreement compared to an ECG; 98%.

To measure core temperature, an ingestible capsule was designed by Mini Mitter Co, and reported by McKenzie and Osgood (2004). This capsule works wirelessly and transmits to an external receiver where the data can be monitored by the user. The capsule remained within the user for around 48 hours before passing, and the results display high degrees of accuracy, with a mean difference of 0.04° Celsius (McKenzie & Osgood, 2004). However, the accuracy of capsules can be comprised if the user was to ingest a cold liquid (Sparling et al., 1993). Another method of monitoring temperature is via an armband, which records peripheral temperature rather than core. Although a good indication of peripheral temperature is given through an arm band, they are often uncomfortable for the user and can cause irritation to the skin (Drenowatz & Eisenmann, 2011; Li et al., 2016).

Within sport, wearables are becoming increasingly popular due to their benefits of providing real-time data, being relatively small and portable compared to current systems, and being more accessible to a greater range of users (Adesida et al., 2019; Cosoli et al., 2022). Many sport coaches adopt GPS vests for their athletes, to monitor distance covered, energy expenditure, and HR (Theodoropoulos et al., 2020). These variables can be monitored live during training and/or performance, which allow the coaches to monitor workload and intensity, and make informed decisions (Ravé et al., 2020; Theodoropoulos et al., 2020). As well as GPS vests, motion sensors can be used to record the motion of an individual, replicating the data produced by more complex and inaccessible optoelectronic camera systems (Adesida et al., 2019; van der Kruk & Reijne, 2018). These sensors are relatively small and can either be applied to the user directly or be integrated into a bodysuit that the user would wear (Adesida et al., 2019; Dobkin, 2013). These sensors are more affordable to the user compared to the gold-standard optoelectronic systems, with the data gathered similar in accuracy and reliability (Auepanwiriyakul et al., 2020). However, as with all technology, the wearable sensors require a calibration process, which if performed inadequately, the data can be significantly worse to that of the gold standard (Adesida et al., 2019; Auepanwiriyakul et al., 2020).

2.2 The Development and Implementation of E-Textiles within Sport

2.2.1 Introduction to E-Textiles

E-textiles are a new form of smart wearables, where the sensor is integrated and often knitted directly into a fabric/garment (Ruckdashel et al., 2022; Zhang et al., 2021). E-textiles have almost limitless uses once fully developed, with a large sector being health monitoring (Zhang et al., 2021). E-textiles work by having electronic/conductive yarn amongst regular yarn, which transmits a signal throughout the garment (Ruckdashel et al., 2022). Along with the material, there is an electronic component to pair with the electronic yarn, which is responsible for transmitting the signal, whilst sending the signal to either a base-station, or a mobile/computer device (Gonçalves et al., 2018). Once the signal has been received, the data can either be viewed in real-time if this feature is available, or after the collection process.

E-textiles are constantly being developed and improved, with the hope of integrating technology seamlessly into the user's lifestyle (Zhang et al., 2021). Smart socks, t-shirts, base-layers, shoes, and many more have already been created, with the attempt of true integration (Amitrano et al., 2020; Ghaida et al., 2014; Stoppa & Chiolerio, 2014; Zhang et al., 2021). Smart shoes and socks have been developed to provide the user with gait analysis, as well as a measure of postural control (Amitrano et al., 2020; Ghaida et al., 2014). Through a combination of sensors on the sole of the foot, heel-strike, toe-off, and weight distribution can all be recorded, allowing for stride length, contact time, and many gait parameters to be captured (Amitrano et al., 2020; Ghaida et al., 2014). To ensure the sensors are in the most adequate position and the objectives of data collection can be met, there is usually a length testing process (Ruckdashel et al., 2022). T-shirts and base-layers can capture a wider range of physiological variables, including respiration rate, heart and palpitation rates, peripheral temperature, and muscle activity (Ruckdashel et al., 2022; Singha et al., 2019). As well as performing data collection, some e-textiles have been designed to provide the user with a greater user experience when wearing the garment. Several t-shirts and base-layers have been developed to heat the user when worn, by integrating heating elements within the fabric (Repon & Mikučionienė, 2021)

2.2.2 Comparison of E-Textiles to Current Gold-Standard Methods

As e-textiles are a relatively new form of technology, there is limited research in the area that explores the accuracy, validity, and/or reliability when compared to their gold-standard counterparts. Edmison et al. (2004) compared the results of an e-textile shoe that records an individual's gait, to the current gold-standard within that sector, which is an optoelectronic camera system and moveable force plates. The results demonstrate high levels of accuracy within the e-textile, however identified that additional research should be conducted before commercial use (Edmison et al., 2004). The study highlighted the fact that the sample were all healthy with no known abnormal gait issues, however, the larger population will not always fit within this sample and would therefore not be available to those individuals immediately (Edmison et al., 2004). Instead of textile strains sensors, some e-textile incorporate fibre-optics as the electronic portion of the device (Gong et al., 2019; Issatayeva et al., 2020). Issatayeva et al. (2020) assessed the accuracy of multiple e-textiles that measure respiration rate, with results not clearly identifying whether the garments were successful or not. Results identified that some breaths were easily identifiable and were extracted correctly, with other sensors not working as properly intended (Issatayeva et al., 2020).

To record the motion of an individual, the most common form of sensor within the e-textile would be a textile strain sensor (Amitrano et al., 2020; Totaro et al., 2017; Zhang et al., 2021). An e-textile developed by Totaro et al. (2017), incorporated three textile strains sensors on the anterior surface of the patella, with the objective of recording relative knee angle (RKA). When compared to the three-dimensional (3D) motion-capture system, one of the three textile strain sensors records RKA with high degrees of accuracy (RMSE [root mean square error] = <4°), with the remaining two sensors not as sensitive to detect the change in RKA. Furthermore, Totaro et al. (2017), developed an e-textile that is worn on the ankle, with the premise of capturing dorsi/plantarflexion, rotations, and adduction/abduction. Likewise with the knee garment, the ankle garment shows high levels of accuracy when compared to the 3D motion-capture system (RMSE = <4°). Li et al. (2020), also devised two e-textile garments, one for the elbow and one for the knee. Both garments were created to measure joint angle, whilst the knee garment was designed to also measure step count. The results demonstrate high levels of accuracy and agreement between their purpose-built goniometer and the elbow garment, with relatively small mean differences observed (0.31°-0.54°) (Li et al., 2020). Furthermore, the knee garment was able to successfully identify and count the steps of the participant whilst walking, running, and climbing stairs.

2.2.3 Current Limitations to E-Textile Adoption

As of 2023, there is yet to be a break-through e-textile that is used within the sport and exercise environment. A large factor to this is the drawbacks and negative connotations that are associated with e-textiles. When creating a new piece of technology, there must be a period of reliability and validity testing before the product can go to market (Luczak et al., 2019). This period can be lengthy and when major issues within the technology can arise unexpectedly, which can further delay the release and adoption of e-textiles (Cesarelli et al., 2021). To conduct the reliability and validity testing, the equivalent gold-standard should be adopted within the research as this will be essentially what the e-textile is seeking to replace (Adesida et al., 2019; Luczak et al., 2019). However, these systems are often inaccessible due to a wide array of reasons (for example, complexity to operate, cost, location) and can make quantifying the reliability and validity not possible (van der Kruk & Reijne, 2018). Gold-standard systems are also often confided to laboratory settings, which does not replicate that of how athletes and individuals move and perform during competition (van der Kruk & Reijne, 2018). This poses another significant challenge and problem to e-textile creation as there will be little ecological validation carried out; an essential part of research and development (Amitrano et al., 2020; Cesarelli et al., 2021).

2.2.4 Knitted Intelligent Textile Tracker

The Knitted Intelligent Textile Tracker (KiTT), as seen in figure 1, is a smart wearable device created by Footfalls and Heartbeats (UK) Limited (*Nottingham, UK)*, which acts as a non-supportive knee sleeve, that collects numerous kinematic variables. KiTT is a development and progression of a previous technological exploration, of an elbow garment (Isaia et al., 2020; Isaia et al., 2018). The original elbow sleeve was created to measure kinematic variables, investigate the mechanical properties of the knit structure, as well as test the durability of the structure through substantial wash testing. To measure an individual's kinematics, a textile strain sensor is incorporated within the fabric, with an electronics unit placed on the upper lateral segment which measures the change in voltage experienced throughout motion (Isaia et al., 2020). This strain sensor requires conductive yarn which is knitted amongst the same yarn of the main garment. Within KiTT, the strain sensor is situated anteriorly to the patella to accurately monitor changes in motion. Following post-processing, the observed change in voltage can be translated into practical variables such as range of motion (degrees), movement breakdown (eccentric:concentric timings), relative velocity, and rest-time. As a technical development, KiTT houses a 9-axis IMU within the electronics module. The IMU has a tri-axial accelerometer, gyroscope, and magnetometer, to measure accelerations, angular velocities, and relative position compared to a calibrated frame (Liang et al., 2022). The current electronics module samples data at 30Hz.

Figure 1: Anterior view of KiTT.

2.3 Rationale for Research

A semi-structured interview allows for a rapport to be developed between the interviewer and the respondent, which can increase the validity of the answers given (Bell et al., 2016; Smith & Sparkes, 2016). These types of interviews have become the most common interview method to collect within the last decade, due to the value of data gathered (Hoeber & Shaw, 2017). Spil et al. (2019), conducted research investigating the current adoption and diffusion of wearables. Semi-structured interviews were conducted to understand the individuals needs and requirements from a wearable, as well as any barriers to adopting wearables within their daily life (Spil et al., 2019). The results of this work identified that wearables need to be reliable, relevant to the specific demographic, and easy to use. The data gathered from the interviews provide researchers a helpful insight into future development of new wearables. In addition to this, research conducted by Rapp and Tirabeni (2020), investigated what amateur and elite athletes would desire within a smart tracker/wearable. The results present that individuals prefer motivational messages before and during workouts, habit trackers, and tools that positively influence their mental wellbeing (Rapp & Tirabeni, 2020). Semi-structured interviews provide the most valid, and valuable data to researchers, with the benefits of this method vastly outweighing alternative methods (Bell et al., 2016; Smith & Sparkes, 2016). Once a need for new technology has been identified, there should be a validation process to ensure the technology is reliable and accurate (Tanner et al., 2015). The current research project aims to bridge a gap through two separate studies, by assessing the need for additional sport technology, and ultimately validating the technology in areas stated by the end-users.

Chapter 3: Engaging end-user, and key stakeholders in the development of a smart kinematic knee sleeve.

3.1 Introduction

As discussed in section 2.1.3, wearable sensors are widely adopted within applied sports settings to monitor workload and training progressions, as well as tracking live variables such as distance covered, calorific expenditure, and HR (Adesida et al., 2019; Luczak et al., 2019). Examples of wearable sensors include HR sensors, GPS, and smart watches, which provide objective data from the users where the resulting data can be used to inform decision making for training and/or competition (Schneider et al., 2018; Seshadri et al., 2021; Theodoropoulos et al., 2020). Furthermore, wearable sensors provide the user with accurate, real-time and objective data, which is often more user-friendly by integrating a more simplistic user-interface with key variables at the fore-front, rather than over-indulging the user with complex variables that are present with more gold-standard methods (Adesida et al., 2019; Aroganam et al., 2019; van der Kruk & Reijne, 2018).

Existing and detailed data collection methods such as 3D motion-capture often require a lengthy process of system/sensor calibration and analysis, to ensure data collected is accurate and valid (Schurr et al., 2017; van der Kruk & Reijne, 2018). As well as calibration time, the user should have specialist knowledge to understand the relevant post-processing procedures, to firstly understand how to use the system, as well as ensuring the data is valid. Systems such as 3D motion-capture are also often inaccessible due to the complexity of the systems and the cost associated with purchasing, operating, and licensing (Schurr et al., 2017; van der Kruk & Reijne, 2018). Wearable sensors negate the main drawbacks and allow the users to understand the key variables in real-time, allowing for changes in technique/performance to achieve the goals of the session and subsequently increase performance.

In addition to regular wearable sensors, knitted sensors, also known as e-textiles, provide the user with real-time data from a user-interface that is simple and effective, by wearing what appears to be an ordinary garment or item of clothing (Ratten, 2020; Wilson et al., 2017). E-textiles are purpose-built garments that have electronic yarns incorporated to enable data collection (Adesida et al., 2019). The Hexoskin is an example of an e-textile which is capable of capturing respiratory rate and HR, as well as other physiological variables (Elliot et al., 2019). Additionally, more research and development e-textiles include base-layers to monitor HR, respiration rate, echocardiograph data, as well as socks that can monitor gait patterns whilst running and walking (Adesida et al., 2019; Elliot et al., 2019; Stoppa & Chiolerio, 2014). The use of electric/conductive yarns are often hidden or integrated with the design pattern and offer the same level of comfortability as a regular garment without electric yarns (Gonçalves et al., 2018; Simegnaw et al., 2022).

E-textiles are an extension and continuation to wearable sensors, and are just one example of wearable sensors, that allows the user to wear a single garment, rather than affixing an external sensor to existing clothing (Li et al., 2019; Wang et al., 2020). This increases the user’s comfortability when performing motion, which allows their established movement patterns to be executed, rather than adopting an alternate movement pattern due to being uncomfortable (Li et al., 2019; Myer et al., 2014;

Williams et al., 2016). To support this notion, Jayasinghe et al. (2019) investigated whether there is a difference between affixing sensors onto garments compared to an individual’s body. The results present minor discrepancies between affixing markers onto clothing compared to the body, providing further evidence that e-textiles provide valid measurements when created to replicate a garment.

When new sports wearables are in development and aim to be incorporated within applied sport and exercise environments, there needs to be collaboration between the creators/developers, researchers, and the end-users (Adesida et al., 2019; Luczak et al., 2019). Dialogue created through interviews and focus groups between the developer and end-user, allows for the technology to be more user-friendly, relevant, and specific within applied sport, and suit what the end-users require (Adesida et al., 2019; Luczak et al., 2019). To gather information from end-users, researchers can employ numerous methods such as questionnaires, focus groups, and market research to answer important questions related to the design, function, and usability of the technology (Carlin et al., 2015; Nibbeling et al., 2021; Ratten, 2020). To conduct an interview, one of the four main methods can be utilised (SI, SSI, UI, and FG). Structured interviews allow the researcher to follow an interview schedule, with only the questions listed being asked (Evans et al., 2021; Smith & Sparkes, 2016). In addition to this, the interviewer cannot ask follow-up questions which may be of importance, due to the strict nature of structured interviews (Skinner et al., 2020). Should the interviewer wish to ask follow-up questions, and deviate from the interview schedule, a semi-structured interview may be more suited to the research (Gill et al., 2008; Skinner et al., 2020). The respondent should not deviate from the course of the interview schedule, with no extended dialogue permitted (Evans et al., 2021). The data collected from a structured interview is often biased to one side of a topic, whilst the respondent may typically not be able to express their views and/or feelings about an issue (Bell et al., 2016; Skinner et al., 2020). When following an interview schedule with no follow-up questions, the respondent can often feel cornered, which can affect the validity of the results. Furthermore, the interviewer and respondent may not develop a rapport, which can further affect the validity of the results in relation to the research aim (Bell et al., 2016; Skinner et al., 2020).

In contrast to structured interviews, unstructured interviews offer the respondent majority of the control, due to no fixed questions organised by the interviewer (Jamshed, 2014). Data gathered from is suited to specific research questions, focussing on understanding an individual's thoughts and beliefs, as well as their reactions to certain topics (Jamshed, 2014; Pedersen et al., 2020; Smith & Sparkes, 2016). This type of data is purely qualitative, with little concern for numbers and statistical analysis (Smith & Sparkes, 2016). On the other hand, focus groups are conducted to collect specific data from several participants in a timely manner, as well as understand how people perceive specific answers (Nyumba et al., 2018; Smith & Sparkes, 2016). There are specific questions involved within a focus group to direct the interview in a certain direction, with the interviewer listening rather than asking the majority of the questions (Smith & Sparkes, 2016). Instead, the respondents essentially conduct the interview amongst each other, with the interviewer recording key answers (Nyumba et al., 2018; Smith & Sparkes, 2016).

Researchers often utilise semi-structured interviews to gather sufficient data from the end-user as there are often pre-determined concepts and thoughts need to be explored and discussed (Gill et al., 2008; Skinner et al., 2020). Semi-structured interviews allow the researcher to follow a set interview-schedule, where key questions can be asked and answered. Unlike other interview methods, the interviewer and interviewee is allowed to deviate from the interview schedule to give additional information that might be relevant to the intended question (Skinner et al., 2020). This information may not have been previously considered by the researcher and developers and can serve extremely useful within the development (Skinner et al., 2020; Smith & Sparkes, 2016; Spil et al., 2019). By allowing the interviewee to provide additional information, the creators may gain additional insights that were not previously mentioned and can allow for more targeted use and development of the technology specific to the users.

As well as qualitative data collected through interviews, valuable data can be collected from literature, and systematic reviews (Adesida et al., 2019; Powell et al., 2021). Reviews provide the researcher with large amounts of data and key findings within specific areas, allowing for current and future research to be created and disseminated (Dyer, 2015; Powell et al., 2021). Gathering valuable data from end-users allows for specific development of new technology, making the technology applicable to specific sporting situations and environments (Smith & Sparkes, 2016; Tanner et al., 2015). To gather information from end-users, qualitative methods allow for the most appropriate form of data to be collected for the current research project (Smith & Sparkes, 2016).

During the process of new technological formulation, the context of a targeted sport provides crucial information which is fed back into the development of the technology, to allow the technology to be specific and valuable (Adesida et al., 2019; Spil et al., 2019). Ratten (2020) suggests that the conditions, circumstances, environments, or situations are all important factors into what technology is developed to bring something new to the sports industry. The exact process into how a new technological system is developed has gone undocumented and remains largely unknown (Wilson et al., 2017). The creation of new e-textiles in specific follows a user-centred approach, by involving the end-users throughout the development phase to ensure the device remains applicable and relevant within applied practice (Wilson et al., 2017)

Accordingly, the current research aims to identify the key variables used by end-users within their applied practice. As well as this, the research aims to distinguish whether there is a need for technology that can measure relative knee angle (RKA) in applied sport in the form of an e-textile. Strength and conditioning coaches are responsible for testing athletes and collecting the data by using technology such as Gym Aware, and motion-capture systems. By creating dialogue with the strength and conditioning coaches who are ultimately a key end-user group, the results can be fed-forward into the following study and aid the development of strategies to quantify the reliability and validity of KiTT.

3.2 Methods

3.2.1 Participants

Ethical approval was given by the College of Science and Engineering Research Ethics Committee at the University of Derby (ETH2122-0737: 11th March 2022) for the current research project. All participants provided informed consent electronically [appendix a], after reading the participant information sheet [appendix b]. The study followed an inclusion criterion, with all participants required to have experience: working with athletes (past or present); data collection (past or present); > 1 year of working within a professional team environment.

3.2.2 Recruitment

Participants were recruited for the research project in several ways. Social media was used to contact potential participants that fit the inclusion criteria. Established relationships from the researchers, and the industry partner were contacted about the research project and their potential involvement. Upon providing informed consent prior to and during the interview, participants received the most recent version of KiTT (*Version 16.3*) as sections of the interview were concerned with the device (Figures 1 and 2). However, participants were not sent the electronics for the current research project due to technical developments on-going on the device at the time of data collection. As a result of this, participants were not able to receive a full experience of KiTT and the system which may have influenced the quality of data.

Figure 2: Demonstration of KiTT applied to an individual's left knee.

3.2.3 Interview Schedule

The interview schedule was devised by the research team and industry partner, to suit a semi-structured interview style. Some questions within the schedule are brief to allow for conversation to develop (DeJonckheere & Vaughn, 2019). The interview schedule included 28 questions and four sections: participant background, use of technology, impressions of KiTT's physical appearance, and market research [appendix c]. The four sections covered wide areas that are key in determining a potential use-case for KiTT within an applied setting. The interview schedule for the current project was adapted from a previous schedule created by Footfalls and Heartbeats (UK) Limited, which had been used internally for market research purposes.

3.2.4 Data Analysis

Once all interviews had been recorded, the raw recordings were saved and anonymised through their individual unique ID. Following anonymisation, the recordings were transcribed by TP Transcription Services (*Pen y Banc, Denbigh, Wales*), to allow for thematic analysis. Upon receipt of transcriptions, each participant was emailed their individual transcript from their interview to check for accuracy against their responses given. After the participants confirmation of their answers, raw recordings were with transcripts analysed to identify the key themes throughout the interview. Open-ended questions were analysed following guidance from (Braun & Clarke, 2006) thematic analysis framework. After familiarisation of the data, preliminary codes were created, and data was organised into the specific sections. Codes were then analysed, and themes were then identified and defined. Thematic analysis was adopted to provide an overall image of responses, with regards to KiTT and it’s use within applied sport.

3.3 Results

3.3.1 Descriptive Characteristics

Twenty participants were contacted for participation within the research project, with 11 participants recruited (100% male; age = 34.3 ± 8.0 years; combined experience within a sporting environment = 48 years; average experience within a sporting environment = 4.4 years). All participants met the inclusion criteria, with 2 participants not currently engaged within professional team sporting environments, but they have held similar positions prior to their current roles. Several participants stated that in their current situations, they are actively working more than one job. Approximately 63% (n = 7/11) of participants were current strength and conditioning coaches. Two participants were currently working as performance analysts, with 63% of participants working within 'other' job roles. Other job roles were defined as: basketball head coach (n = 2), head of performance in basketball (n = 1), sports programme director of a private school (n = 1), academy director of an under-16 academy school (n = 1), osteopath (n = 1), and senior lecturer (n = 1), as observed in table 1. Participants provided answers across three main sections, where six main themes have been generated.

Table 1: Masked participant ID's and their current job role/title.

Participant ID	**Current Job Role/Title**
Participant 1	Strength & Conditioning Coach
Participant 2	Head Basketball Coach
Participant 3	Strength & Conditioning Coach
Participant 4	Programme Director at Strength & Conditioning Company
Participant 5	Academy Director at Private Firm
Participant 6	Personal Trainer/Strength & Conditioning Coach
Participant 7	Working in Applied Healthcare in Private Firm
Participant 8	Head Basketball Coach
Participant 9	Academic within a UK University
Participant 10	PE Teacher/Provision of Strength & Conditioning Sessions
Participant 11	Strength & Conditioning Coach

Following thematic analysis, three main themes were identified, with a total of six subthemes; two subthemes per theme, which can be identified can be observed in Figure 3.

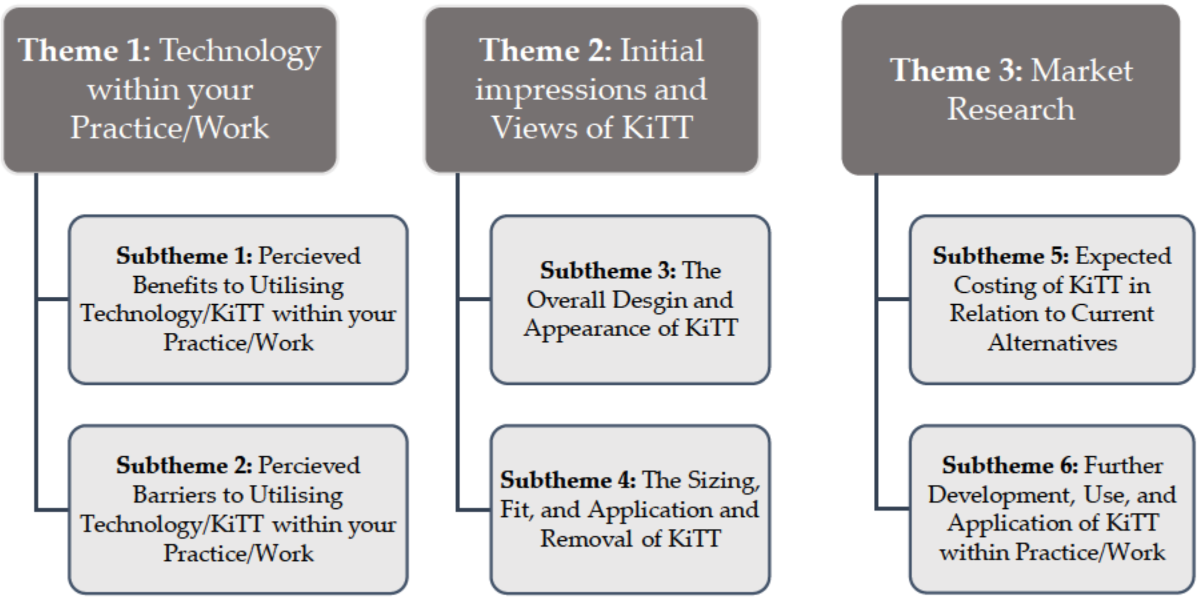


Figure 3: Flow chart illustrating the themes identified within the relevant sections of results.

3.3.2 Theme 1: Technology within your Practice/Work

3.3.2.1 Subtheme 1: Perceived Benefits to Utilising Technology/KiTT within your Practice/Work

Participants were asked whether they currently or have previously used 'timing gates' (n = 5, 45%), 'force plates' (n = 3, 27%), 'video analysis systems' (n = 5, 45%), 'velocity measurement tools' such as 'GymAware' (n = 4, 36%), 'jump mats' (n = 5, 45%), and 'wearables' (n = 1, 9%). Participants explained numerous potential benefits to utilising technology within their practice, with benefits outweighing the potential drawbacks/negatives:

'...progressions able to be tracked through numbers rather than word-of-mouth...' [Participant 1]

'Increases performance and training' [Participant 3].

> *'I'm a strong believer in tech/ It [technology] can see things in a way we can't see, it [technology] can measure things we can't measure, I don't think we use enough of it within our lives'* [Participant 11].

Technology has been used within sport and exercise since the 1970's, with uptake increasing dramatically in more recent years (Gao & Lee, 2019; Ruth et al., 2022; Woessner et al., 2021). The amount of technology utilised within applied work, is largely dependent on the practitioner's personal preference and their coaching philosophies (Jones & Wallace, 2005). Depending on the task being conducted, the use of technology can also vary. For example, if an individual is investigating an individual's biomechanics for a specific sport, the number of markers required for motion-capture systems can range from 16-33 (Choo et al., 2022; Ito et al., 2022), where marker occlusion can lead to invalid data (Adesida et al., 2019). To combat this, wearable sensors are being created which aim to overcome the issues faced by motion-capture systems. As well as combating marker occlusion, wearable sensors are often designed to be discreet, compact, and wireless, allowing a full range of motion to be executed, increasing the validity of the data; including both e-textiles and more traditional variations of wearable sensors such as sports watches and HR straps (Adesida et al., 2019). To complete a movement that often involves marker occlusion, sport wearables can enable a task to be completed without the potential of data loss.

When discussing the provision and importance of real-time data, participants described the benefits:

> *'Real-time data is more beneficial as athletes often ask about results there and then, even if the data is very simple. Take the jump mat for example, "how high was that?"*

Athletes will often try and beat it and make competition with each other, which can lead to increased performance and training. Some see the data as motivational, and some see it as intriguing' [Participant 3].

'Real-time data helps as feedback can be given and help drive intensity, which serves as a motivational tool' [Participant 5].

'... it makes the job a lot easier. Some of the athletes buy into it as well if it's on a screen right in-front of you, which is quite useful in that situation. Especially if you're doing jump testing in a team of rugby/American football athletes for example. You can get them to challenge each other which is quite useful' [Participant 1].

'Strength and conditioning sessions are limited on time and it's easier to have real=time data rather than record and analyse retrospectively, which is more time consuming. It gives more time to focus on programming rather than looking at the data' [Participant 4].

Real-time data is seen to help coaches on numerous fronts, with time being saved analysing data retrospectively which allows for other tasks to be completed in the same period (Adesida et al., 2019). Furthermore, when data is presented instantaneously, there is a greater 'buy-in' from the participants/athletes due to the competitive nature of individuals, especially when in large groups (Windt et al., 2020). Depending on the task being carried out, real-time data can serve as a helpful tool to coaches and individuals by encouraging competition and giving feedback instantly (Adesida et al., 2019; Van Hooren et al., 2020). Within gait analysis, real-time feedback is given through an IMU to enable the participant to alter their technique for performance and pre-habilitative gains (Dingwell & Davis, 1996). Research has identified that when real-time feedback is not available, participants may become exposed to overuse injuries, poor technique becoming ‘natural’, and not reaching their full physiological potential (Sallis et al., 1992; Van Hooren et al., 2020). Sport wearables allow the individual to monitor their technique to avoid learning improper movement patterns which can lead to injury, as well as exerting themselves to their limit, increasing performance gains (Sallis et al., 1992; Van Hooren et al., 2020). However, as e-textiles do not have the amount of supporting research which other technological systems, there is not a guarantee that injury prevalence will be reduced, but instead this finding can be inferred.

3.3.2.2 Subtheme 2: Perceived Barriers to Utilising Technology, and KiTT within Practice/Work

When discussing the adoption of technology within participants’ practice/work, numerous barriers were identified, with some of the reasons including:

> *‘This sort of technology [jump mats and timing gates] would be beneficial to use within my practice, however due to time constraints this isn’t ideal’* [Participant 3].
>
> *‘Cost, accessibility, usability, validity, and reliability, are the barriers to technology usage’* [Participant 11].
>
> *‘Rarely get access to these spaces due to availability and cost associated with systems, such as Vicon and Force Plates’* [Participant 6].

Seven participants (63%) reported that within their current roles, there is not enough time to adequately set-up technological systems and make the most of a session where time is already limited/restricted. Cost was reported to be a substantial barrier to 27% (n = 3) of participants, with 18% (n = 2) of participants reporting the complexity of some technological provisions as a barrier. Additionally, the lack of research and evidence-base into technology would be a deterrent for practitioners to implement technological methods within their practice. To avoid exploring technological avenues that will not meet the desired objectives of the user, new technological systems need to be researched to solidify its use-case and purpose (Windt et al., 2020). This allows the device's limitations to be identified whilst ensuring it will be fit for a specific purpose (Peake et al., 2018; Windt et al., 2020).

As KiTT is a new data collection tool that is largely still in early development, and not ready for general sale, there is currently limited research supporting the accuracy, validity, reliability, and application of the technology. However, future research aims to address this issue, by specifically looking into the accuracy, validity, and reliability of KiTT. The current research project aims to address the potential need for KiTT by collecting qualitative data from potential end-users. This is also the case for similar devices that are at a similar stage within the respective development phase (Whitelaw et al., 2021). Four participants (36%) reported that the lack of evidence would be a reason not to use KiTT within their practice:

'Something [KiTT] I would use within my practice if there was evidence-based practice and enough supporting literature. It would be used alongside concurrent practice, and would be interesting to have sensors on multiple parts of the body' [Participant 6].

'Would implement within practice if evidence base and research was present' [Participant 7],

however, 27% of participants reported that the lack of evidence would not be a barrier to adopt such technologies within their practice/work:

> *'Any small variables we can use to progress we'll take a gamble and take a chance, even if there is no evidence to support the use of KiTT'* [Participant 2].

> *'If it [technology] is new and upcoming, I would spend no more than £50, but if there is research and evidence, and word-of-mouth etc, I would spend a bit more'* [Participant 10].

To resolve some of the barriers presented by participants, 'longer time with athletes' (longer or increased frequency of sessions) may allow for greater uptake of technology as the coach will be able to set-up the systems, to ensure data can be collected in a timely manner. Furthermore, additional research into the validity and reliability of KiTT would serve as beneficial, as a lack of evidence is observed as a barrier to technological uptake. Finally, more cost-efficient, and simple technological solutions should be considered when executing data collection. Simple technological solutions are often more streamlined and have been developed with the end-user in mind, making the user interface more user-friendly and easy to use, reducing the time taken to set-up the system (Adesida et al., 2019).

The current research project involved all partici

3.3.3 Theme 2: Initial Impressions and Views of KiTT

3.3.3.1 Subtheme 3: The Overall Design and Appearance of KiTT

Participants provided honest thoughts and opinions on the overall design and appearance of KiTT, from both a coach, and a player's perspective. Within the National Basketball Association (NBA) elbow and knee sleeves are becoming increasingly common for numerous reasons ranging from support, preference, and physical appearance (Dickerson et al., 2020). The design of a smart knee sleeve that has the potential to be adopted within professional team sport environments, need to be both designed and received well. Eight participants (73%) believed KiTT to be designed well:

> *'It is an appealing design. Is it something the players find 'cool' and wear during training and games?'* [Participant 6].

> *'Nice design and I like it. Nice look and feel. As an athlete I would wear it, as a coach, it's comfortable'* [Participant 8].

> *'It's an appealing design, athletes more than ever love this type of stuff. Accessory heavy, might get a large buy-in, simple, neutral design. Athletes seem to like the bright colours and designs'* [Participant 2].

However, participants had contrasting thoughts and views, regardless of their initial thoughts of the design:

> *'As an athlete, they may want something a bit brighter, but most athletes wouldn't really care too much about it as long as it helps with their training'* [Participant 3].

> *'...could look snazzier, but there's no need really. Could even personalise it with team colours etc...'* [Participant 10].

> *'bland [design] but doesn't need to look jazzy. Some players have the preference of looking jazzy, ability to have personalisation might make this more interesting. If it does the job then not fussed how it looks'* [Participant 11].

The design is crucial in terms of functionality and how often the individual would wear the garment (Goncu-Berk & Tuna, 2021). When designing an e-textile, the conductive yarns need to be positioned correctly to allow the movement and change of tension to be detected. If the conductive yarns are not positioned correctly, the data produced will ultimately be less valid and reliable (Goncu-Berk & Tuna, 2021; Mishra & Kiourti, 2019). Ensuring the conductive yarns are in the correct position with the correct tension and stitch length, ensures the data that is collected is at the highest degree of validity. Furthermore, the physical appearance will largely influence the individual's choice to wear the garment which is ultimately required to collect data. To ensure for appropriate physical design, engineers should liaise with potential end-users to ensure it will be well recovered by the desired audience (Adesida et al., 2019; Zhang et al., 2021). Although the current physical design of KiTT is not as appealing as other wearable technology, the scope for further development and advancement is limitless with personalisation possible through advanced knitting methods.

3.3.3.2 Subtheme 4: The Sizing, Fit, and Application and Removal of KiTT

To collect data regarding the sizing, fit, application and removal of KiTT, participants were sent a version of KiTT in either size small, or medium. This was communicated prior to postage to ensure the correct size was distributed to the participant. Once KiTT had arrived, participants were asked to try the sleeve on prior to the interview. There were no restrictions to the duration and what activity was performed during this time. To help with placement, participants were emailed a series of photographs detailing how to correctly wear the sleeve, these photographs can be seen in Figure 2. With regards to the length of KiTT, 45% of participants explained that they felt the knee sleeve was too long:

'Very long, but I am really so short so could be because of my height. For taller athletes the length would probably be okay' [Participant 3].

'Prefer not to be as high on the thigh – personal preference' [Participant 8].

'Slightly longer than knee supports worn in the past but its not uncomfortable because of. Not bulky, covered more of the calf than I would be used to' [Participant 9]..

Five participants (45%) explained that the length was appropriate for the desired purpose, and that it was not uncomfortable despite the material covering up to half of the thigh, and the upper third of the shank. To ensure KiTT remains in the correct position during sporting movement, silicon bands were fitted to the upper and lower bands of the sleeve. Other wearable sensors and e-textiles have utilised silicone to act as a sensing layer, provide rigidity, or to attach electronic components to a material (Harito et al., 2020; Ismar et al., 2020). When asked about the silicon bands on KiTT, 100% of participants responded positively to the addition:

''It's comfortable. Silicon gets a good grip, might start to pull on leg hairs depending on the force placed through the sleeve' [Participant 8].

'Silicon didn't give any problems and the sleeve didn't move at all throughout the sessions' [Participant 7].

'Top and bottom silicon bands area a good idea, material like other garments which also feature bands so it's a good feature' [Participant 4].

There is often a challenge to correctly fit a garment with silicon support, due to the tension and support that it brings (Ismar et al., 2020). However, when discussing the application and removal of KiTT, eight participants reported that there were 'no problems', and that the sleeve was 'easy to take on and off'. However, 27% of participants responded with contrasting answers, and that the silicon bands:

> *'... a little bit more uncomfortable than the fabric but assume it's their to keep it there and grippy, the main fabric is comfortable'* [Participant 9].

> *'Comfortable and easy to take on and off, the silicon was irritating at start but once sorted it was fine to wear. Would like to wear and use if didn't have to send back'* [Participant 11].

Within the strength and conditioning community, knee sleeves are used widely to provide additional support to individuals when lifting heavy weights (Mortaza et al., 2012). However, as KiTT's main purpose is a data collection tool rather than a knee support, participants reported that there wasn't a great level of support:

> *'Players are comfortable with wearing sleeve like this in games and training, don't think they offer too much support, so something like this would be okay'* [Participant 1].

> *'KiTT not as thick as other sleeves which isn't as supportive, but doesn't lead to bunching at the back of the knee'* [Participant 7].

When creating an e-textile, the sensors often need to be either in extremely-close contact, or in-direct contact within the skin to capture data (Goncu-Berk & Tuna, 2021). A key property to knitted garments is that they are tight whilst still allowing for a degree of stretch, creating a perfect environment for integrating electronic yarns and materials (Jansen, 2020). Research by Ketola et al. (2020), demonstrated that e-textiles are proven to work better and provide more reliable readings when the fabric is tight and elastic, rather than being relaxed and loose fitting. A loose and relaxed fit allows for crumpling within the fabric, which ultimately effects the responsiveness of the sensor (Ketola et al., 2020). As KiTT is an e-textile, the structural properties of the fabric allows for accurate data to be gathered, as well as providing a level of comfortability to the individual (Simegnaw et al., 2021; Vowles et al., 2022).

3.3.4 Theme 3: Market Research

3.3.4.1 Subtheme 5: Expected Costing of KiTT in Relation to Current Alternatives

As KiTT is largely still in development, participants were asked how much they would expect to pay for the technology as a package, as well as what a recommended retail price for KiTT should be. This serves as vital information as all participants have experience with technology and costings. Responses ranged from ‘£50 for the sleeve’, and ‘£2,000 for the sleeve and electronics’, with no clear agreement/consensus in the price. However, participants explained that electronic components and software is often the most expensive part of sport technology, with some performance analysis software being in the region of five figures. To put costing into perspective, some performance analysis software has a yearly charge of £3,458 (ex. VAT), with 3D motion-capture systems costing more than $150,000.

One participant gave a detailed response, that put the price point of KiTT into the context of an individual purchasing the sleeve. The participant explained that KiTT should be priced depending on the desired demographic rather than a standard, fixed cost for all demographics/target audience. For example, a participant explained that if a potential consumer had undergone private knee surgery/replacement that cost '>£10'000', the consumer would be inclined to buy technology such as KiTT that could help with their rehabilitation if the price tag was '~£400'. On the other hand, if a potential consumer had undergone knee surgery/replacement on the NHS, the consumer may be less inclined to pay the '~£400' that a private patient would:

'Context is important and would need to be priced in double figures rather than triple' [Participant 4].

'If someone has had £10,000 knee surgery, £400 price tag knee sleeve to ensure physio works is not an issue, but if surgery is free on NHS, this £400 price-tag can be a bit steep' [Participant 11].

3.3.4.2 Subtheme 6: Further Development, Use, and Application of KiTT within Practice/Work

Due to the nature of the semi-structured interview, participants were able to provide additional information and feedback on KiTT that wasn't within the interview schedule. From their personal, and professional experience, participants described where they think technology like this can be and should be applied in the future:

'I think something like this [KiTT] would be beneficial within my practice, especially within a lifting environment where they are doing squats and other lifts. Potentially more beneficial with more of a workforce (additional coaches) who can review the live data while the sessions being run' [Participant 8].

'Any squat, jump, uni-lateral based movements would be sufficient. Exercise progressions would serve as valuable technology, able to monitor whether load can be increased etc…' [Participant 4].

In addition to this, participants identified that KiTT could be used to monitor fatigue and changes in movement strategies:

'KiTT could identify any potential injury risk factors and changes in movement strategies due to fatigue and would serve as hugely beneficial for this and being able to monitor load. Micro-changes in depth not visible to the human eye, however KiTT can detect these changes between repetition, and this can help the coach inform training' [Participant 4].

Düking et al. (2016) concluded that to monitor fatigue most effectively within an individual, multiple wearables should be adopted, whilst considering not making the individual too uncomfortable with excess devices. To achieve this, KiTT serves as a viable solution to allow the individual to remain comfortable, by wearing only one sensor and wearable to collect kinematic data. A combination of wearable sensors in the form of GPS, HR straps, and IMU's may provide the individual with a larger bank of data following a movement but may result in compromising the comfortability of the individual (Düking et al., 2016).

To aid coaches to monitor fatigue, participants responded that a live dashboard would be beneficial to them, which is like GPS software. A dashboard would allow coaches to monitor workload, training intensity, as well as other key variables related to the individual wearing the technology. As the data is collected in real-time, coaches can instantaneously monitor and manipulate training:

'If an athlete says an exercise is quite hard but they aren't presenting that way on the data, changes can be made to go heavier/lighter. Helps to prevent over-progression in a small time-frame. Help tailor training a lot better' [Participant 2].

A key benefit to KiTT compared to other data collection systems, is the capture of the human body rather than an external body. KiTT records the data of the individual, whereas velocity-based technology such as GymAware, records the velocity of a barbell (O'Donnell et al., 2017). To give a true reading of the velocity of the participant, the technology should monitor the individual rather than the bar/equipment (Sánchez-Medina et al., 2017). KiTT allows for velocity of the user to be captured, which will aid athletic progression through more accurate training plans.

KiTT has the potential to collect data in real-time whilst providing feedback to the user which can aid training and ultimately performance. Participants described that when an individual is squatting to a certain depth, it would be 'beneficial' to have a method of feedback that informs the user they have reached the desired depth, and can begin the upwards phase of the repetition:

> *'real-time feedback of identifying to athlete when they have reached a certain depth and can begin to go upwards would be beneficial'* [Participant 3].

As well as this, participants explained that KiTT can be used to help with tempo-training, by monitoring and controlling the downwards and subsequent upwards phase of a squat. The feedback can be given in a similar manner for squat depth, with a traffic light system illuminating at key points during the movement i.e., the correct speed, and squat depth would display green. A system like this would be beneficial to individuals as they will be unable to closely examine the output variables during an exercise, especially if the load is high/the task being performed prevents the athlete from accessing the phone/tablet displaying the variables.

3.4 Conclusion

The results display a clear need for additional e-textiles to be created, to help to eliminate barriers posed by traditional and current data collection systems. E-textiles are more affordable, easier to use, portable, and made with the end-users in mind; an attractive proposition for current strength and coaches (Adesida et al., 2019; Luczak et al., 2019). Participants highlighted that KiTT can and should be used within squatting exercises, and additional lifts within strength and conditioning environments. This will be a prevalent point within study 2, with the exercises informed from the results of study 1. As well as exercise selection, study 1 will inform the data analysis portion of study 2 with regards to the identifying the required variables and informing the research output (what future work should be conducted). Following on from coaches stating that micro-changes in technique only being visible to technology, reliability and validity are key underpinning aspects that are required before KiTT can go to final development and market for end-users to purchase and use.

Outside of the scope of the next study, but for future research, KiTT should be put in-front of those that will wear the technology, the players. Getting the players' views and understanding will help increase the level of agreement between coaches and players which may lead to an increased buy-in. Internal development into the software and system will also be ongoing following the answers from participants, with alterations to real-time provisions, and suggestive methods and analysis techniques, both being developed as the project progresses.

Chapter 4: Testing the Reliability and Validity of the Kinematic Knee Sleeve

4.1 Introduction

As highlighted throughout the thesis, the use of technology in sports performance has increased exponentially due to the increased demands of sport and drive for excellence within athletes (Ride et al., 2013; Tjønndal, 2022). As a result, coaches, teams, and athletes, are adopting data driven approaches to inform training and to maximise performance (Dyer, 2015; Gamble et al., 2020). Technology acts an integral part of almost every sport, where 9/11 coaches currently use technology within their work, as identified in chapter 2. The benefits of technological adoption (e.g., monitoring training load, applying additional training stimuli, and provide a deeper level of data analysis), far outweighs the negatives and drawbacks, which is an influencing factor into implementation (e.g., additional time constraints, the potential for data overload, and misinterpretation of results) (Gamble et al., 2020; Windt et al., 2020). More recently, technology has been developed to allow for the user to wear devices, rather than perform tasks in specific environments around the devices; these are known as sports wearables (Adesida et al., 2019; Ride et al., 2013). Inertial measurement units can be attached to the user, which provide coaches with accurate detail into an athlete's biomechanics and ultimately informing whether any alterations in training can be made to increase performance (Ride et al., 2013). As well as IMU's, GPS, and HR straps, have been developed and employed to allow the user to perform their sporting task within the desired environment, rather than within a fixed, controlled environment (Adesida et al., 2019; Ravé et al., 2020; Theodoropoulos et al., 2020). End-users will adopt several technological methods within their practice for numerous reasons, such as, to monitor training workload, increase the efficiency of an athlete, or to collect specific biomechanical data (Adesida et al., 2019; Pendergast et al., 2006; van der Kruk & Reijne, 2018).

Global positioning systems are commonly used within a wide range of sports, enabling coaches to monitor the intensity and workload of an athlete during any sporting situation (Ravé et al., 2020; Theodoropoulos et al., 2020). Furthermore, GPS' provide a high degree of accuracy and validity outdoors, however, when the technology is required for indoor use, the system is not able to provide the same level of accuracy and validity due to the connection between sensor to satellite being obstructed (Krenn et al., 2011; Ravé et al., 2020; Theodoropoulos et al., 2020). Heart rate straps allow the HR of an individual to be tracked with extreme accuracy, however the scope of variables captured is restrictive due to the basic nature of the device (Pasadyn et al., 2019). However, HR serves as a vitally important tool for coaches when prescribing training plans and monitoring workload, as the variable can be used to prescribe training zones, training plans, and monitor an individual's development throughout a training block (Diaz et al., 2015; Pasadyn et al., 2019). Inertial measurement units are a relatively new development compared to previous methods, with the user often affixing multiple units to their limbs/body to track motion (de Almeida et al., 2021; Dong et al., 2020). Whilst providing accurate data, IMU's can require complex calibration processes which if not performed correctly, will influence the data that is captured (de Almeida et al., 2021; Dong et al., 2020)

More recently, a new generation of sports wearables, termed e-textiles, are being developed with the aim of eliminating the barriers/issues with more traditional static and portable data collection systems (Adesida et al., 2019; Stoppa & Chiolerio, 2014). E-textiles incorporate conductive yarns and sensors within a fabric, that can be worn as a regular garment (Adesida et al., 2019; Gonçalves et al., 2018; Haddad et al., 2020; Simegnaw et al., 2021). E-textiles have the capability to be used within almost any environment, as there is usually only one main requirement to a functioning system; to wear the garment (Adesida et al., 2019; Cesarelli et al., 2021). The application for e-textiles is almost limitless, with the possibility of capturing cardiac (Postolache et al., 2014), kinematic (Li et al., 2020), respiratory (Ferreira et al., 2016), muscular (Jin et al., 2019), skin temperature (López et al., 2010), and more (Liu et al., 2012; Vu & Kim, 2020). Additionally, e-textiles often serve as cheaper, more portable, and user-friendly alternatives to more traditional data collection systems (Adesida et al., 2019; van der Kruk & Reijne, 2018). One specific e-textile that can record specific physiological variables is the Hexoskin. The Hexoskin is a type of compression vest that has the capability to monitor specific variables such as minute ventilation, breathing rate, and energy expenditure (Haddad et al., 2020; Montes et al., 2018). As well as this, several smart socks have been developed to measure gait parameters, and provide informed decisions that allows for self-correction (Semjonova et al., 2022). Additionally, postural assessment data can also be extracted from a smart sock through machine learning and the appropriate algorithms, which will be masked for the end-user, with only the relevant output data being visible (Adesida et al., 2019; Amitrano et al., 2020).

As e-textiles are relatively new compared to alternative data collection systems, there are often issues within the initial design process (Adesida et al., 2019; Stoppa &

Chiolerio, 2014). If the conductive yarns are not structured or positioned correctly, the output data could be excessively noisy, and/or not detect the desired responses, which could ultimately lead to less valid data (Adesida et al., 2019; Amitrano et al., 2020; Haddad et al., 2020; Stoppa & Chiolerio, 2014). However, all e-textiles aim to eliminate the problems that are present with more traditional data collection systems, by encouraging the user to wear the garment as regular clothing, rather than needing to be strapped into specific equipment and/or have upwards of 10 markers attached to their body (Adesida et al., 2019; Stoppa & Chiolerio, 2014; van der Kruk & Reijne, 2018). This allows the user to perform the required motion in the same manner as in a competition, increasing the validity of the data. Furthermore, the user will not be connected to cables, leads, and require external markers and additional sensors to be attached, increasing the comfortability when performing the task (Stoppa & Chiolerio, 2014; van der Kruk & Reijne, 2018) However, for e-textiles to replace the current systems, there needs to be a period of validation assessment to ensure the output data is meeting the objectives that is required by the user and provides a high degree of accuracy.

Before new sports technology is made publicly available, there should be a period of validation, where the gold-standard counter-part is used to test for accuracy, reliability, and validity, to ensure that the desired objectives are met from the new device (Adesida et al., 2019; Aroganam et al., 2019). KiTT has the potential to be used within a wide range of environments, including strength and conditioning, rehabilitation, physiotherapy, as well as clinical settings. Following discussions with end-users, the proposed study has been developed and tailored to assess the reliability and validity of KiTT, against the current gold-standard criterion method, Vicon. To assess the degree of reliability and validity, numerous sporting exercises that are commonly adopted within applied practice will be employed, which in turn could lead to increased ecological validity.

4.2 Methods

4.2.1 Participants

Prior to recruitment, ethical approval was given by the College of Science and Engineering Research Committee at the University of Derby, in line with the Declaration of Helsinki (ETH2122-0396: 23rd November 2021, ETH2122-2537: 10th February 2022, and ETH2122-4556: 6th July 2022). All participants provided written and verbal informed consent before participation within the study [appendix A], after reading and acknowledging the participant information sheet [appendix B]. A total of 23 participants were screened to ensure they matched the inclusion criteria:

- aged between 18-65 years;
- completes >150 minutes moderate-intensity exercise per week;
- >2 years' experience within resistance training exercise;
- free from any illness/disease/injury;
- successfully completes a health screening questionnaire [appendix C].

Anthropometric data for the sample can be observed in Table 2.

Table 2: Anthropometric data for the sample (n = 23).

Anthropometric Data				
Gender (M/F)	***Age (Years)***	***Mass (kg)***	***Height (cm)***	***BMI (**kg/m^2**)**
18/5	24.1 ± 4.9	73.9 ± 9.7	175.6 ± 9.7	23.95 ± 2.68

4.2.2 Equipment

The current study aimed to assess the validity of KiTT, against a gold-standard criterion method, Vicon (*Oxford, UK)*. Vicon is a 3D motion-analysis system that records a body's motion, with the ability to record numerous variables simultaneously. Vicon is an optoelectronic system that requires the user to wear reflective markers in pre-determined locations. KiTT developed by Footfalls and Heartbeats (UK) Limited (*Nottingham, UK),* is a smart wearable textile tracker that records changes in resistance in real-time, which can be translated into numerous variables (e.g., RKA, relative velocity of a repetition, eccentric:concentric timings, rep counter) through programmes and machine learning.

4.2.2.1 KiTT Structure

KiTT (*Version 16.3*) was knitted as a single fabric on a Stoll CMS ADF 32 W knitting machine (*Karl Mayer Stoll, Reutlingen, Germany*). The yarn for the main fabric consists of four ends of lycra (22 dtex, Zimmermann, *Weiler-Simmerberg, Germany*) and a cover of polyamide 6.6 (78 dtex, Zimmermann, *Weiler-Simmerberg, Germany*). The upper and lower cuff consists only of Stretchline Elastic 815 (356 dtex). The textile strain sensor is a conductive yarn which consists of silver-plated multi-filament nylon yarn (Statex Shieldex®, 117/17 dtex; electrical resistivity <1.5KΩ/m, *Bremen, Germany*). The transmission lines connected to the strain sensor are also made of conductive silver-plated multi-filament nylon yarn (Statex Shieldex®, 235/36 dtex; electrical resistivity <80KΩ/m, *Bremen, Germany*).

For the current study, KiTT is worn on the participants left knee with the purpose-built electronics module situated to the lateral side of the patella. This prevents the IMU from being obstructed and causing interference/excessive noise within the data. The textile strain sensor is laid anteriorly to the knee-joint, with equal proportions of the sensor above and below the patella to accurately measure joint motion. The fabric is stretched to a comfortable position relative to each participant, to ensure there is no bunching/slack fabric left in the sleeve.

4.2.2.2 Vicon

Vicon Nexus (*Version 2.11, Oxford, UK*) will serve as the gold-standard criterion tool, as this has been used extensively within human research (Armitano-Lago et al., 2022; Herrington et al., 2017; van der Kruk & Reijne, 2018). The set-up of Vicon requires the use of 12 Vicon Vantage cameras, mounted on an overhead rig which is aimed and calibrated. Each participant was required to have 16 retro-reflective markers affixed to key bony landmarks to enable Vicon to identify lower limb segments. Reflective markers were affixed following the "Plug-In GAIT Lower-Body AI" template, created by Vicon Nexus. For this template, markers were affixed to participant's: ASIS (anterior superior iliac spine; bi-lateral; n = 2); PSIS (posterior superior iliac spine; bi-lateral; n = 2); KNE (lateral epicondyle of the tibia; bi-lateral; n = 2); ANK (lateral malleoli; bi-lateral; n = 2); TOE (base of the 2nd metatarsal; bi-lateral; n = 2); and HEE (calcaneus; bi-lateral; n = 2). Four references markers were attached to the participants thigh (THI; bi-lateral; n = 2) and tibia/shank (TIB; bi-lateral; n = 2), with one limb housing markers on the lower 1/3 of the segments, with the opposing limb housing markers on the upper 1/3 of the segments. Figures 4 and 5 display the locations of reflective markers on each participant.

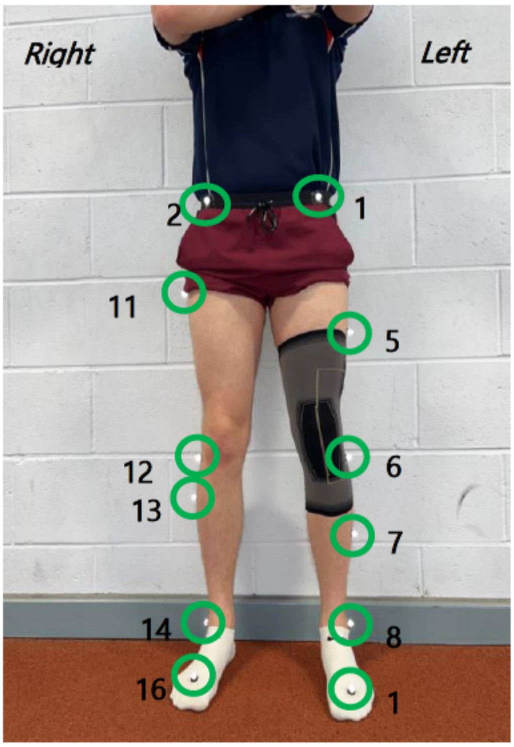


Figure 4: Anterior view of Vicon reflective markers (1 = left ASIS; 2 = right ASIS; 5 = left THI; 6; left KNE; 7 = left TIB; 8; left ANK; 10 = left TOE; 11 = right THI; 12 = right KNE; 13 = right TIB; 14 = right ANK; 16 = right TOE).

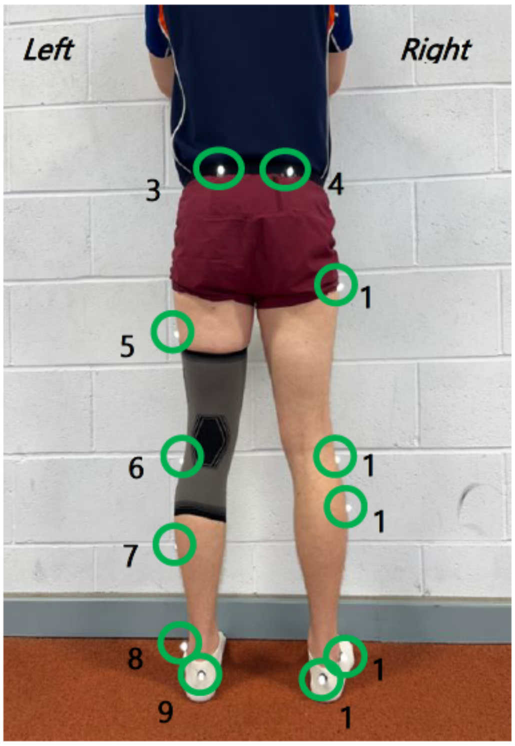


Figure 5: Posterior view of Vicon reflective markers (3 = left PSIS; 4 = right PSIS; 5 = left THI; 6 = left KNE; 7 = left TIB; 8 = left ANK; 9 = left HEE; 11 = right THI; 12 = right KNE; 13 = right TIB; 14 = right ANK; 15 = right HEE).

4.2.3 Project Developments

Prior to data collection, several pilot studies were conducted to finalise the protocol and ensure all objectives of the study could be met from the data collected. The pilot studies involved the trial of several sport-specific movements that arose during interviews with applied practitioners in Chapter 1. These sport-specific movements included walking, running, a hopping test, agility trial, and a box-drop (BD). Through the data gathered, KiTT at the current sampling rate (30Hz) was not sensitive enough to detect changers in gait for both walking and running, as well as an agility trial. The hopping test required the participant to complete three hops on the same leg, however, due to the space required for Vicon to record and capture in, this was not possible. After trialling the BD, the data gathered was representative of the motion that was performed and was deemed most appropriate for the research project.

Once the sport-specific movement was defined, a range of heights were tested, ranging from 3″ – 21″. A height of 15″ was found to be the most optimum height, as it allowed for participants to walk off the box and land comfortably on both feet at the same time. A lower box reduced the amount of time participants had to land with both feet, with a higher box increasing the load on the participant's lower limb's per landing. To control the tempo of each movement, numerous metronome settings were trialled, ranging from 30-100 beats per minute. A tempo of 45bpm was found to be a simple timing pattern to stick to, with the average squat taking as long as three clicks. This allowed each of the movements to be controlled, and easily replicable in following sessions. A slower timing pattern slowed the movement too much so that it wasn't natural, with a faster timing pattern becoming confusing through an increase in the frequency of clicks per repetition. To control the depth, a fixed dowel rod connected to two supports was found to be the best option. This allowed for Vicon heel markers to remain visible instead of being blocked by an opaque/solid depth control measure, such as a chair/bench/plyometric box.

To extract RKA from KiTT's raw resistance readings, multiple Python (Version 3.11, *Delaware, United States*) and MATLAB (Versions R2022a & R2022b, *Massachusetts, United States)* scripts needed to be created. Python scripts were purpose-built for this research project, to allow for resistance to be translated into RKA. At each repetition, one peak RKA from Vicon was correlated to a trough in KiTT's raw resistance. For example, a Vicon peak RKA of 110° was correlated to a KiTT's raw resistance of 38Ω (Figure 6). This process was repeated for all 8 repetitions per exercise, creating core values where raw resistance can be translated into a predicted angle for KiTT. This allowed KiTT's raw resistance to be completely translated into a predicted angle and allow for direct comparisons with Vicon's data. After a predicted angle trace was calculated, scripts in MATLAB allowed for peak angles to be identified and extracted. The MATLAB process was automated through a signal processing toolbox, where values above and after a custom threshold were identified (Figure 7). The threshold values allowed for only peak angles to be extracted, by removing additional peak angles that were not valid.

Once Python and MATLAB scripts were finalised for the research project, there was further development into whether additional sporting variables could be extracted. Following on from Chapter 1, MATLAB code was developed to try and extract velocity from the weighted back squat (WBS). However, velocity extraction was not possible due to a relatively low sampling rate. To test the capabilities of KiTT, Footfalls and Heartbeats (UK) Limited created a 100Hz electronics module to replace the current 30Hz module. After conducting further pilot testing, the 100Hz was sensitive enough to extract velocity within the WBS, countermovement jump (CMJ), and the squat jump (SJ), with similar peak angle differences between KiTT and Vicon to that of the 30Hz electronics module. Due to the variable nature of the leg curl (LC), neither the 30Hz nor the 100Hz electronics units were sensitive enough to detect the overall velocity of the repetitions. As data collection for the research project had already commenced, and the 100Hz electronics module was largely un-tested, all data collected for the research project was done with the 30Hz electronics module, with velocity not calculated.

A drawback that should be taken into consideration with KiTT, and potentially a wider case of e-textiles, is the ‘dead-space’. This is where there is no reliable or accurate data captured, due to the bunching in the fabric. During previous work, the dead-space within KiTT was from 0-45°. However, due to technological and physical developments, the dead space has been constricted to 0-30°. Within this region, the textile strain sensor is unable to detect any changes in kinematics, however the IMU is still sensitive enough to detect angular change. For any exercises that incorporate moving from full extension to a period of <50°, the angular kinematic from the textile strain sensor may not be reliable and valid. However, for exercises that incorporate a range of motion >40°, there is an increased chance that angular change can be quantified reliably and accurately.

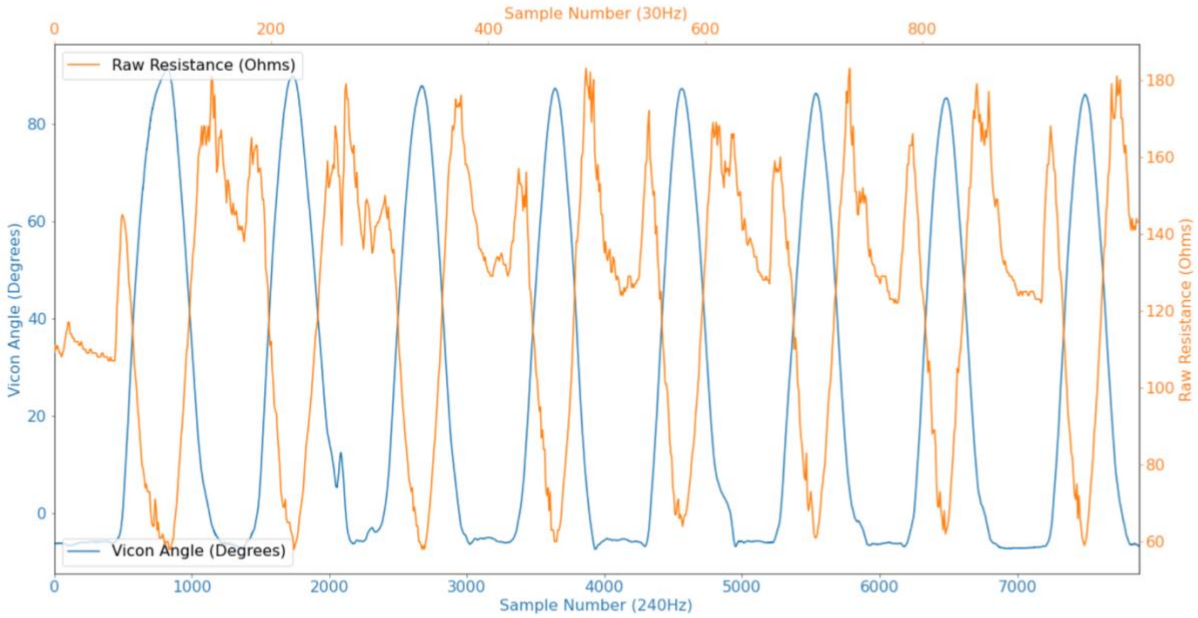
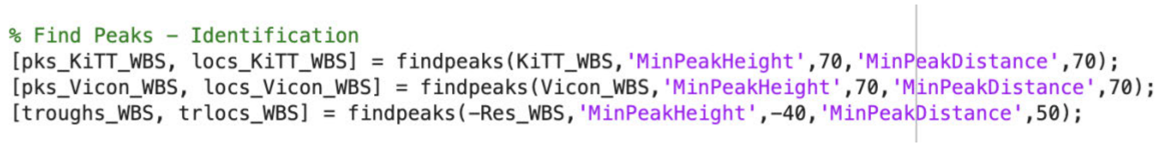


Figure 6: Excerpt of python code which align's the two files together (Blue line = Vicon RKA; Orange line = KiTT raw resistance).



```
% Find Peaks - Identification
[pks_KiTT_WBS, locs_KiTT_WBS] = findpeaks(KiTT_WBS,'MinPeakHeight',70,'MinPeakDistance',70);
[pks_Vicon_WBS, locs_Vicon_WBS] = findpeaks(Vicon_WBS,'MinPeakHeight',70,'MinPeakDistance',70);
[troughs_WBS, trlocs_WBS] = findpeaks(-Res_WBS,'MinPeakHeight',-40,'MinPeakDistance',50);
```

Figure 7: Excerpt of MATLAB code that identifies peak values within a specific data frame. The above example is identifying peaks following a WBS, within 'KiTT_WBS' (KiTT predicted RKA), 'Vicon_WBS' (Vicon RKA), and '-Res_WBS' (KiTT raw resistance). Res_WBS is -Res_WBS as this inverts the data, and trasnaltes the troughs into peaks.

4.2.4 Protocol

The current study required participants to attend the University of Derby on three sperate occasions. All sessions involved data collection, where the five exercises were completed once in a randomised order with eight repetitions per exercise. Movements were randomised through a random number generator, with each exercise being designated a number (WBS = 1; CMJ = 2; SJ = 3; LC = 4; BD = 5); each number would be drawn once. If duplicate values were present before all five movements were, they would be removed. The first session allowed extra time for familiarisation, which allowed the participants to practice the exercises required, as well as becoming familiar with the data collection equipment and protocol. The exercises for session one were performed in a pre-determined order, to aid the participants in becoming familiar with the required technique. Following a self-prescribed warm-up, and prior to completing any exercises, participants completed five bodyweight squats to ensure the signal of KiTT was appropriate and did not display any excessive noise, and that the data gathered was valid. This was determined when the noise within the signal did not fluctuate to extreme levels (+30 Ω from the baseline signal; pre-determined value that would demonstrate a jump of ~50%), and when the trough's remained constant without fluctuations (Figure 8). A jump of ~30Ω from baseline-peak resistance is an indication that the sleeve is not fitted correctly, likewise when the troughs are noisy and not constant. This was conducted to minimise the chance of invalid data being collected. If excessive noise was present, KiTT was checked to see if there were any creases/bunches within the fabric, if the sensor was positioned correctly, and if the correct size was used.

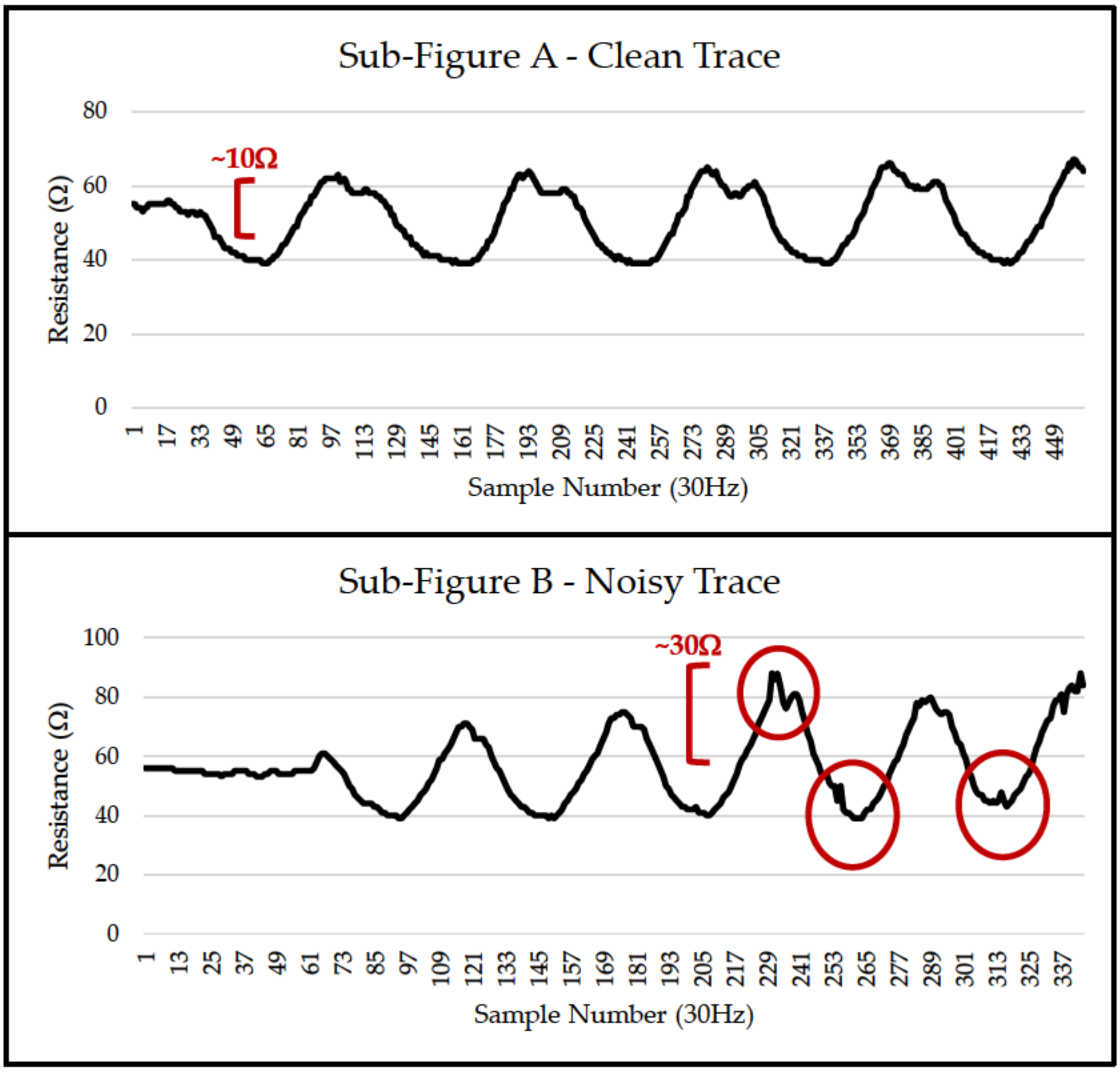


Figure 8: A combination of KiTT's resistance figures for a calibration trial, with sub-figure A displaying clean and acceptable data, with sub-figure B displaying data that is considered as noisy (+~30Ω).

4.2.4.1 Sporting Movements

Five sporting exercises were included within the research project, that are widely adopted within strength and conditioning environments. There were four traditional exercises and one sport-specific exercise. The four traditional exercises were: WBS; CMJ; SJ; and LC. The sport-specific exercise was a squat landing from a 15″ plyometric box (BD). Each sporting movement was performed 8 times to allow for creation of averages, and sufficient comparisons between data collection systems. When performing the WBS, participants executed the movement with a 20kg barbell to add additional resistance and ensure the movements were not completed too fast, and with increased variability from repetition to repetition. Due to machine availability within the performance suite, the LC was modified to use a resistance band fixed to a squat rack. The opposite end of the resistance band would then be attached to an ankle brace which was worn by the participant (Figure 9A and B).

To control movements, the WBS, SJ, and CMJ, involved a dowel rod which would control the range of motion for each repetition (Figure 9C). Participants would touch the rod with the backs of their thighs when at the lowest point of the movement, before returning upwards. This allowed for the depth of movements to be controlled, allowing for more reliable data output. The dowel rod was set at a specific height, that required participants to be reaching the bottom of their squat, at an angle greater than 90°. A depth of >90° is an acceptable squat depth within research (Cotter et al., 2013; Endo et al., 2020). As well as depth control, participants completed specific movements to a set-timer of 45bpm. Following each repetition, participants would allow one click to pass before completing subsequent repetitions. This allowed for peaks to be correctly identified through Python and MATLAB, whilst replicating similar training standards observed within strength and conditioning environments.

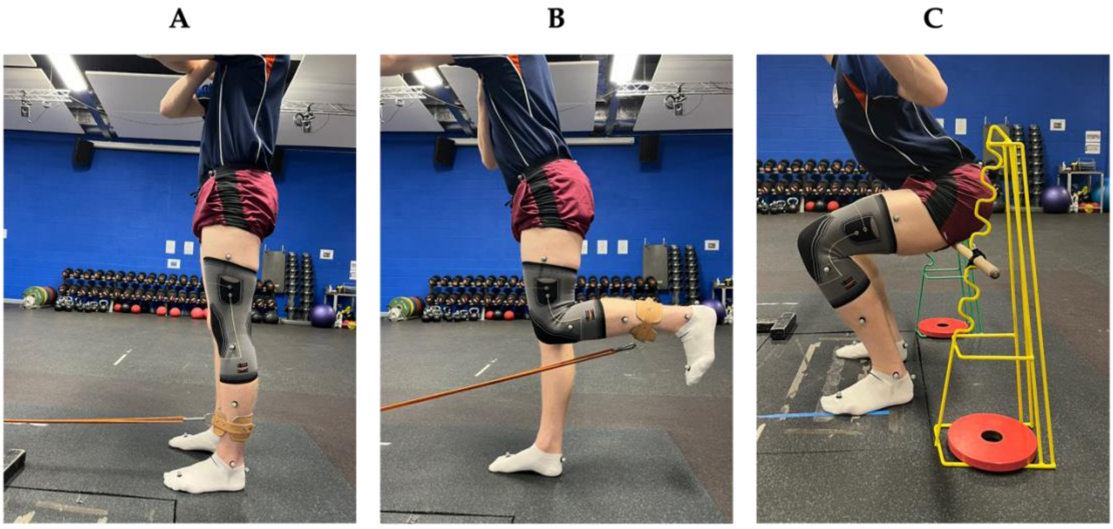


Figure 9: Panel-plot displaying the required movement parameters for each specific exercise. Panel-plot A: Beginning position for the LC. Panel-Plot B: Mid-point (greatest degree of flexion) for the LC. Panel-plot C: Depth control measure that was used for WBS, CMJ, and SJ.

4.2.4.1.1 Weighted Back Squat (WBS)

During the WBS, participants began the downwards phase of the squat on click 1, aiming to meet the depth control rod at click 2. Once the participant met the depth control measure on click 2, participants immediately began the upwards phase of the squat, to full extension (click 3). Before beginning the next repetition, participants would allow for one click in between to allow for balance to be regained. This is a constant theme throughout all five exercises. Figure 10A displays a RKA trace for the amount of expected knee flexion at each respective click.

4.2.4.1.2 Countermovement Jump (CMJ)

The CMJ required more volition from the participant as there was only one click per repetition. When the participant was ready to begin, hands would be fixed on hips with feet shoulder width apart. On a click that the participant felt comfortable, the participant began the downwards phase of the movement, before exploding rapidly upwards to flight, when the participant met the depth control measure. After landing, the participant would wait for as many clicks as necessary, before completing the next repetition on a click. Figure 10B displays a RKA trace for the amount of expected knee flexion at each respective click.

4.2.4.1.3 Squat Jump (SJ)

The SJ followed a similar protocol to the CMJ with hands fixed on hips and acting from volition, with participants beginning the downwards phase on a click of their choice (click 1). Instead, participants would wait at the depth control measure before propelling upwards on the second click; this would require a faster downwards phase to that of the WBS and CMJ. This allows for the stretch-shortening cycle to be disrupted and introducing an isometric hold in a squat position; both which are requirements to the SJ (Kozinc et al., 2022). On the second click, participants would explode rapidly upwards into flight, before landing. After landing, participants would begin the following repetition their own volition. Figure 10C displays a RKA trace for the amount of expected knee flexion at each respective click.

4.2.4.1.4 Leg Curl (LC)

Like the WBS, the LC consists of three evenly spaced out clicks per repetition. Click 1 signifies the start of the repetition, where participants begin to flex the knee and elevate the foot. At click 2, participants should be at maximum knee flexion. Once this click has passed, participants begin to extend the knee back to the starting position; participants should reach this point at click 3. There are no depth control measures present for the LC. Between clicks 1-3, the participant should be moving through flexion and extension as one swift movement without pause/hesitation. Figure 10D displays a RKA trace for the amount of expected knee flexion at each respective click.

4.2.4.1.5 15” Box Drop (BD)

Finally, the BD requires participants to remain stationary at the top of the box to collect baseline values, and act from volition, like the CMJ and SJ. After a stationary period of ~3 seconds, participants put their right foot forwards in-front of the box, before dropping into a squat position on both feet. Once the participant has landed, this position is held for two clicks before standing upright. Once the participant is upright, the repetition can be repeated. Figure 10E displays a RKA trace for the amount of expected knee flexion at each respective click.

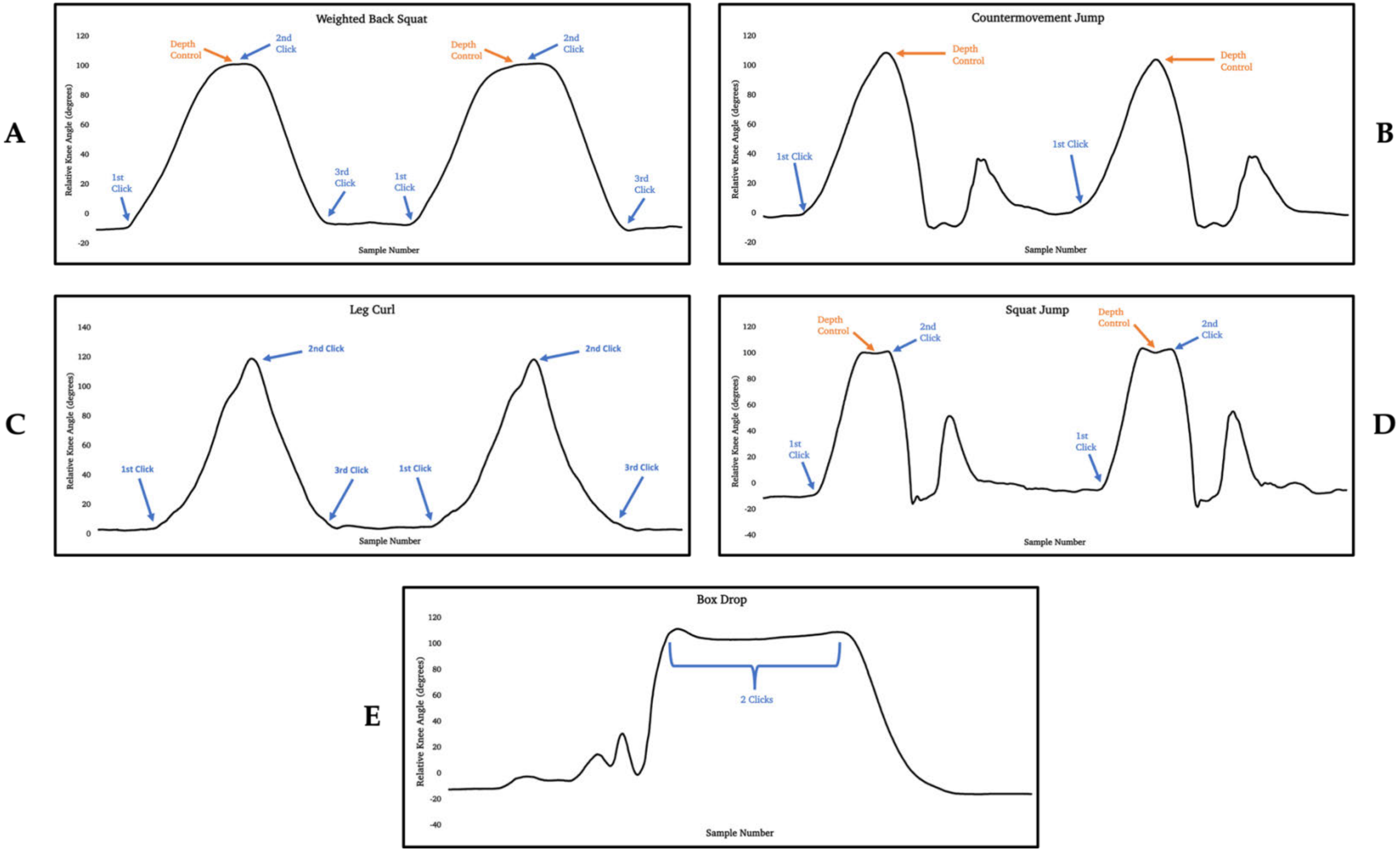

A
Weighted Back Squat
Relative Knee Angle (degrees)
Sample Number
1st Click
Depth Control
2nd Click
3rd Click
B
Countermovement Jump
Relative Knee Angle (degrees)
Sample Number
1st Click
Depth Control
C
Leg Curl
Relative Knee Angle (degrees)
Sample Number
1st Click
2nd Click
3rd Click
D
Squat Jump
Relative Knee Angle (degrees)
Sample Number
1st Click
Depth Control
2nd Click
E
Box Drop
Relative Knee Angle (degrees)
Sample Number
2 Clicks

Figure 10: Panel-Plot displaying five RKA-time traces, and corresponding time-points and/or control measures. (A = WBS; B = CMJ; C = SJ; D = LC; E = BD).

4.2.4.2 Familiarisation

The first visit to the performance suite included participants completing a familiarisation of the exercises which were required, and the equipment that would be used. Within this portion, anthropometric data was collected as well as the dimensions of thigh and shank, and specific characteristics of KiTT when worn. Following the familiarisation, participants were allocated time to practice should they wish to. If a participant was unable to perform the correct technique, verbal coaching points were given until the desired technique was observed. As well as this, participants were also allocated time to become familiar with the equipment that would be used. Each participant was shown the reflective markers, as well as a version of KiTT. Each participant was assigned a specific sleeve that was used for all data collection visits. To avoid overuse, sleeves were labelled and not used for more than the one participant. Additionally, a 20kg barbell for the WBS was kept constant throughout all data collection sessions, along with the strength of resistance band (LC only). Prior to data collection, participants had the chance to ask any further questions that they had.

4.2.4.3 Data Collection Sessions

All sessions involved data collection to assess the reliability and validity of KiTT against a criterion method. Each session was conducted in the same manner, with only the order of sporting movements, randomised. Upon each participant visit to the performance suite, a health screening questionnaire was completed. If successful, the participant would progress to data collection. Depending on the participants prior engagements, a warm-up was recommended to ensure the participant was ready to exercise and take part within the research project. A mix of participants stated that they were previously active in the gym/sports sessions, and felt a warm-up was not necessary. If this was the case, participants would proceed to completing five bodyweight squats wearing KiTT before entering data collection. If participants were not previously active, the warn-up consisted of 5-minutes of cycling at 60 revolutions per minute (rpm) on a WattBike (AtomX). Following the period of cycling, participants rested for 120-seconds before completing low-intensity exercises. These exercises were the same as those within the study, as this allowed participants to be comfortable and ready for data collection. Participants completed the WBS slower during the warm-up, than what was required within the data collection to allow for an increased time-under-tension, allowing for an increased stretch, and greater activation of the muscles around the lower limbs. Participants completed the CMJ and SJ at 50% effort to avoid over-exertion, with the LC and BD completed as expected within the data collection. There was a 30-second rest period between each exercise, where participants completed five reps per exercise.

After the warm-up, participants were given a version of KiTT to wear before affixing the reflective markers. Finally, to ensure the correct size of KiTT was worn by the participant, 5 calibration reps were conducted to ensure the data collected was going to be valid. A final rest period of 2-minutes was given before data collection commenced for the research project.

4.2.5 Statistical Analysis

All movements captured and collected were scrutinised to ensure data was valid without excessive noise and was representative of the exercise that was performed. If there were any marker gaps within Vicon, the gaps were filled through a semi-automated system to ensure the highest degree of accuracy. Gaps were filled following the guidance of van der Kruk and Reijne (2018). Once all gaps were resolved, the "*plug-in gait dynamic"* pipeline was executed to calculate the displacement between each marker, as well as the co-ordinates of each marker per each frame of data captured. Once co-ordinates had been distinguished for each movement, a comma separated value (.csv) file was exported from Vicon which allowed for relevant analysis and comparisons between KiTT. The .csv file contained all co-ordinate data for each reflective marker, as well as a RKA (degrees) for the left limb. Once KiTT data had been captured, the raw output file was checked to ensure there are the correct number of repetitions for the specific movement, and that the resistance trace is representative of the exercise that was performed. All raw KiTT data was automatically saved and exported into a .csv file which allowed for comparisons, and relevant analysis between the gold-standard criterion system.

KiTT automatically records resistance of the textile strain sensor and the changes it experiences throughout a movement. Resistance change was translated into RKA through a purpose-built Python workbook, with peak angles of an exercise identified through MATLAB. Once KiTT data has been translated into RKA, numerous statistical tests will be conducted to assess the degree of reliability and validity of KiTT. Means and standard deviations for each data collection system will be calculated, with the difference between across each exercise. Additionally, reliability and validity tests will be conducted through SPSS for Mac (Version 27, *Chicago, IL, USA*) and Microsoft Excel (Microsoft Corporation, *Redmond, WA, USA)*. Prior to further statistical analysis, tests for heteroscedasticity will be conducted to ensure the right type of data is analysed (Bland & Altman, 1986; Faghy & Brown, 2014). If a positive test is returned, data will be transformed into natural logarithmic data for further analysis (Bland &

Altman, 1986; Faghy & Brown, 2014). Bland and Altman plots were created to better visualise the degree of validity between the systems, as well as producing bias and random error data, as they serve as the gold-standard analytical method to assess validity of a new device (Bland & Altman, 1986).

4.3 Results

4.3.1 Reliability Assessment

Before assessing the validity of a new device, reliability testing must be conducted to ensure the device is reliable enough for use (Pojskic et al., 2019). Following data analysis on 23 participants, 544 peak RKA were calculated for each data collection system which was used to quantify the degree of reliability and validity. To assess the level of reliability, Cronbach's α was used to determine how reliable the results of KiTT are in comparison to the reference, Vicon. Table 3 displays the Pearson's r^2 scores for each exercise, as well as the respective significance values. In addition, the root mean square error (RMSE) values all five exercises were within an acceptable range, suggested by (Rivera et al., 2022) (WBS: 3.28°; CMJ: 4.07°; SJ: 4.08°; LC: 5.00°; BD: 6.78°). The combination of Cronbach's α and RMSE displays that the degree of error was small, demonstrating an excellent level of reliability of KiTT, which can also be observed in regression analysis plots in Figure 11 (Koo & Li, 2016; Rivera et al., 2022).

Table 3: Pearson's r value's, along with the corresponding significance values.

Exercise / Movement	**Validity Assessment**	
	Pearson's r^2	**Sig.**
WBS	0.902	*< 0.001*
CMJ	0.838	*< 0.001*
SJ	0.868	*< 0.001*
LC	0.913	*< 0.001*
BD	0.782	*< 0.001*

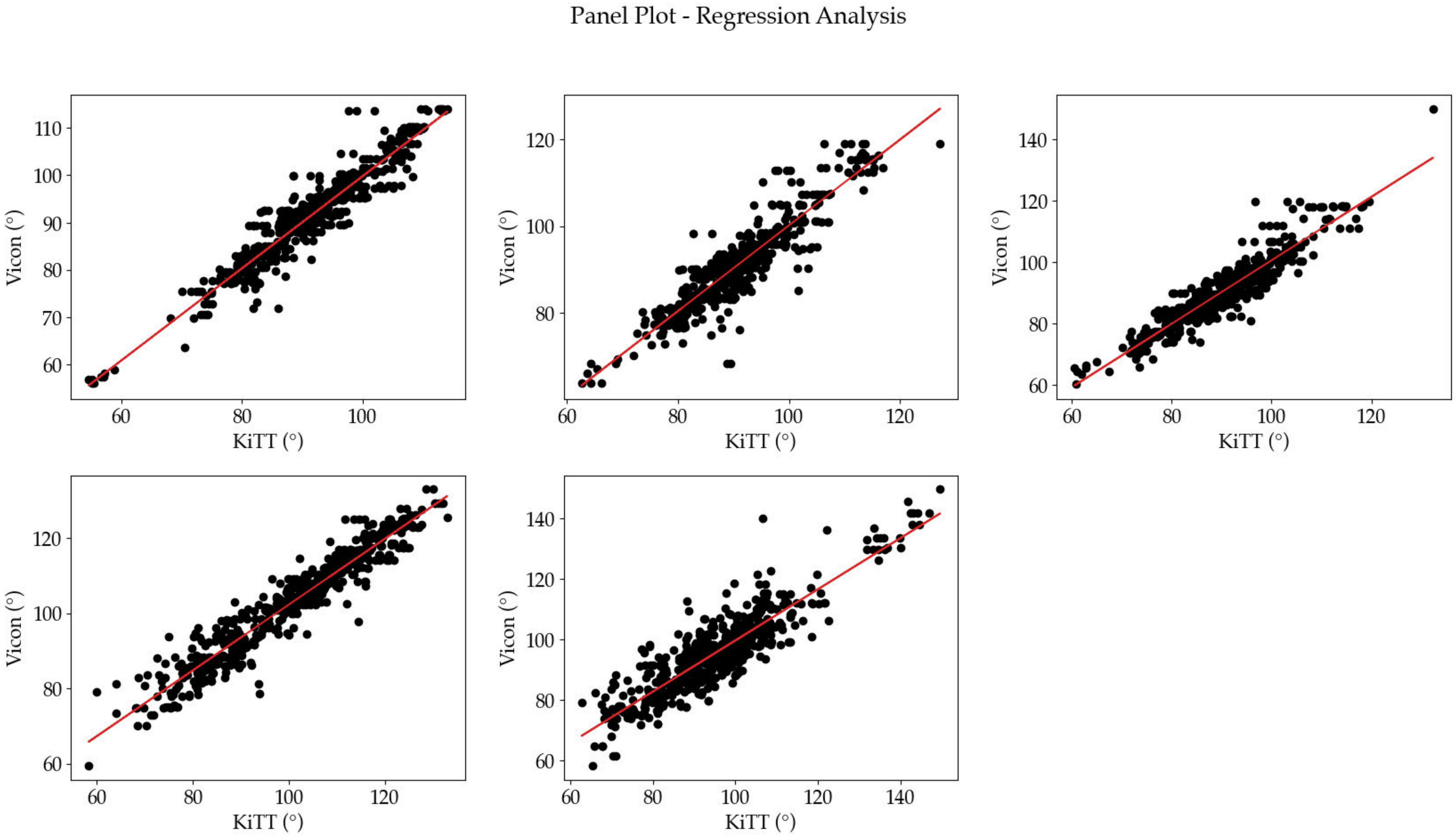


Figure 11: Panel-Plot that displays regression analysis graphs for the five exercises that have been completed within the current study, with the line of best fit identified (Top Left = WBS; Top Middle = CMJ; Top Right = SJ; Bottom Left = LC; Bottom Middle = BD).

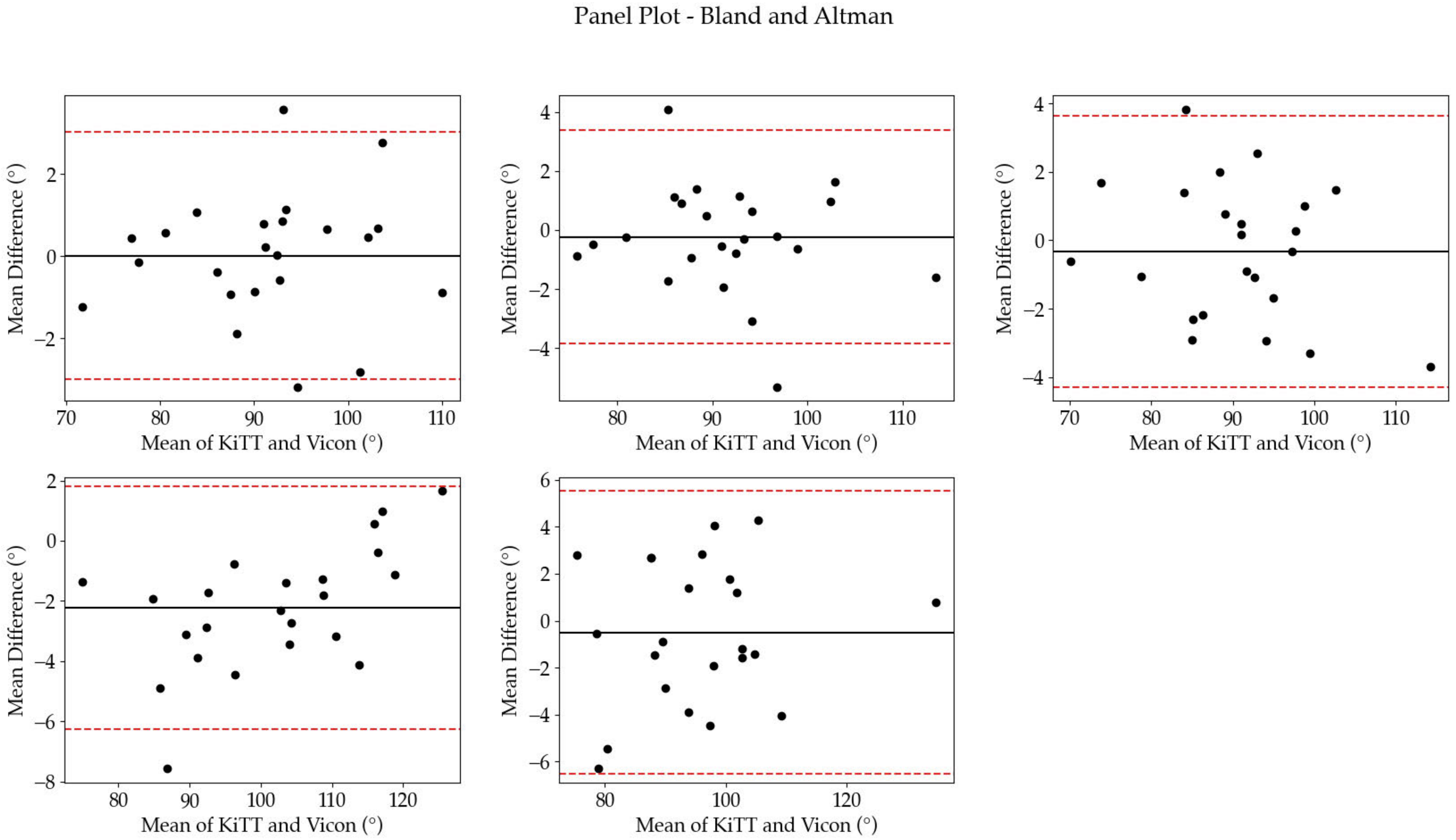


Figure 12: Panel-Plot that displays five graphs for the exercises that have been completed within the current study, with the mean differences, and upper and lower LoA identified (Top Left = WBS; Top Middle = CMJ; Top Right = SJ; Bottom Left = LC; Bottom Middle = BD.

4.3.2 Validity Assessment

The data presented in Table 4 displays averages and standard deviations which were calculated for all exercises, across the three main parameters: Vicon RKA (V), KiTT RKA (K), and Raw Resistance (RR). RR is the direct output from KiTT in its raw form. Like three-dimensional motion-capture systems, variables are often recorded in degrees (°) or degrees per second (°/s). Relatively small differences between Vicon and KiTT were observed, with differences of -0.01° (WBS); 0.27° (CMJ); 0.32° (SJ); 2.23° (LC); and 0.51° (BD).

Table 4: Averages and standard deviations (±) for RKA for Vicon and KiTT, along with the difference between the two systems, and the raw resistance from the specific frames where RKA was extracted.

Exercise / Movement	Relative Knee Angle			
	Vicon (°)	KiTT (°)	Raw Resistance (Ω)	Difference (°)
WBS	91.40 ± 10.19	91.39 ± 10.45	44.74 ± 11.30	0.01
CMJ	91.33 ± 9.34	91.60 ± 10.09	46.47 ± 11.51	-0.27
SJ	90.45 ± 10.08	90.77 ± 11.18	45.37 ± 12.03	-0.32
LC	100.67 ± 15.04	102.90 ± 13.77	42.39 ± 11.91	-2.23
BD	95.18 ± 14.35	95.69 ± 13.71	43.14 ± 1.37	-0.51

To further determine the validity of KiTT, Bland and Altman plots were created through MATLAB to display the level of agreement between the two systems. Furthermore, regression analysis was conducted through SPSS for Mac to identify the statistical value, and significance. Table 5 highlights the Cronbach α values for the five exercises, as well as the corresponding significance values. The sport-specific exercise, BD, as well as the CMJ and SJ, displayed a high positive correlation between KiTT and Vicon, according to boundaries established by Mukaka (2012). Additionally, the WBS and LC displayed a very-high positive correlation between KiTT and Vicon (Mukaka, 2012). Figure 12 displays the five sporting exercises amongst a panel plot, highlighting the mean difference between the two systems, the 95% confidence intervals, and an absolute 0° reading. Panel-plots A-D display at least one point outside the confidence intervals, with panel-plot E displaying all data points within the confidence intervals (Figure 12). These graphs indicate high to very-high degrees of validity between the two systems, with minimal bias present. However, KiTT displays a bias within the LC exercise, with a value of -2.23°, indicating an over-estimation of the peak RKA. As panel-plot E (Figure 12) has wider limits of agreement (± 6°) compared to panel-plots A-D (± 2° - 3.5°), validity is weaker within the LC even though all points are within the limits. Within practical settings, all exercises are deemed as valid due to a small error region (± <6°) which is relatively small enough to not impact training or performance.

Table 5: Cronbach's a value's, along with the corresponding significance values.

Exercise / Movement	**Reliability Assessment**	
	Cronbach's a	**Sig.**
WBS	0.974	0.902
CMJ	0.954	0.838
SJ	0.962	0.868
LC	0.975	0.913

BD	0.938	0.782

4.4 Discussion

4.4.1 Key Findings

The primary aim of the study was to investigate the reliability and validity of a smart e-textile in comparison to a gold-standard reference system. KiTT displayed high degrees of reliability and validity = across all five sporting exercises when measuring RKA, with KiTT displaying very-high correlations within the WBS and LC, with the remaining three exercises displaying high correlations, respectively. Raw results between KiTT and Vicon portray that the peak angle are similar, with a maximum difference between the systems being present within the LC (-2.23°), and the minimum difference within the WBS (0.01°) (Taborri et al., 2020). These results signify the validity and accuracy of KiTT when compared to a gold-standard reference, with reliability remaining excellent through all sporting exercises.

4.4.2 Validity and Practical Applications of KiTT

Across five commonly adopted sporting exercises, KiTT displayed high to very-high levels of reliability and validity. For coaches and end-users, this information is crucial into the adoption of sport technology, as without reliability and validity, objectives may not be met, and data can be misinterpreted. Prior to adoption of new sport wearable technology, extensive research into the reliability and validity needs to be carried out (Adesida et al., 2019). Wider research has demonstrated that wearable systems have been assessed for validity, with Roell et al. (2019), investigating the validity of a new IMU system. The results of this system display r^2 values of 0.76 – 0.95, demonstrating the validity of KiTT within the current study. Furthermore, specific e-textiles in the form of socks, have been validated and show that foot performance and gait patterns can be analysed through an array of strain sensors (Januskevica et al., 2020; Oks et al., 2020)

3D motion capture systems such as Vicon, are renowned for the validity and accuracy that is provided across a wide range of sporting movements (Tak et al., 2020; van der Kruk & Reijne, 2018). Knee flexion angles are found to have the smallest margin of error for such systems, with the difference often being no more than ~1° (Tak et al., 2020). The accuracy offered by Vicon is in-line with the accuracy of KiTT, where a mean difference of 0.01° was identified across the whole sample. Additional research has suggested that when performing a squatting task that is recorded via an optoelectronic system, an error range of <2° is considered acceptable, with 2-5° considered as reasonable (Tak et al., 2020). This is due to the phenomenon described as soft tissue artefact (STA), where reflective markers may move slightly during motion, which ultimately reduces the accuracy of the motion captured (Ancillao et al., 2021; Tak et al., 2020; van der Kruk & Reijne, 2018). According to Ancillao et al. (2021), the STA phenomenon appears to have the largest influence on the thigh cluster, with overall ranges from 4-18mm, an error range of 10°. As KiTT is a textile, there are no reflective markers required for motion capture, which eliminates the STA phenomenon, reducing the possibility of inaccurate data.

To better inform coaches of how their athletes are training and progressing, KiTT can serve as an all-in-one tool that collects, monitors, analyses, and stores data, whilst providing metrics in real-time. This form of technology is not common within applied practice, with often multiple systems and pieces of software required to match that of KiTT, which is like GPS, and HR straps (Ravé et al., 2020; Theodoropoulos et al., 2020). Within both strength and conditioning, and clinical environments, practitioners often have to utilise numerous pieces of equipment, which can take time away from data collection and the participants (Cheng & H M Bergmann, 2022; Seshadri et al., 2021; Wilson, 2008). To have the possibility of a single piece of technology that would satisfy the need's to collect, monitor, analyse, and store data would be fundamental moving forward, and serve as a largely desired piece of equipment amongst many coaches and practitioners (Luczak et al., 2019; Windt et al., 2020).

As KiTT is still a relatively new piece of technology, there hasn't been extensive research into the full capabilities of the technology. From the results of the study, KiTT can be adopted within numerous areas, including strength and conditioning, physiotherapy, clinical practices, team-sessions and many more (Albasini et al., 2010; Harris et al., 2010; Luczak et al., 2019; Røe et al., 2019). However, unlike technology that is currently in use and popular amongst all environments, there needs to be sufficient evidence and research supporting the technology. Since its inception, GPS has accumulated more than 1500 research articles, with more than 200 specific articles related to the GPS technology, creating a substantial and significant research and evidence base, giving practitioners the confidence that they system is robust and reliable (Cloosterman et al., 2022; Malone et al., 2017; Theodoropoulos et al., 2020; Zhang & Poslad, 2013)

4.4.3 Alternative Solutions to KiTT

The current study has displayed that KiTT has comparable results to that of the gold-standard methods, whilst costing just a fraction of the price. In addition, KiTT serves as a more streamlined technological solution, with minimal set-up required before data collection can commence. In contrast to this, gold-standard 3D motion-capture requires the participant to be fitted with several reflective markers on specific bony landmarks, as well as a length camera, and user calibration process, before commencing data collection (Taborri et al., 2020; van der Kruk & Reijne, 2018). Having the option to collect data quickly, in a short time frame is key to strength and conditioning sessions, who have minimal time to monitor and develop their athletes (Ebben et al., 2005; Weldon et al., 2022). Research has eluded that little time is given to strength and conditioning sessions during the in-season, with these sessions conducted on the same day as other sessions (i.e., technical, or review), which reduces the adaptations that could be made by the individuals (Ebben et al., 2005; Nakata et al., 2013; Spaniol et al., 2010). Therefore, having a device that has the capability of testing multiple athletes across a wide range of movements in a fraction of the time currently, will serve extremely useful to users and coaches (Fernandez-Fernandez et al., 2014).

Within sport and exercise, there are numerous technological solutions that can capture, storing, and analysing sporting motion (Adesida et al., 2019; Luczak et al., 2019; van der Kruk & Reijne, 2018). The current gold-standard methods are often expensive, inaccessible, and require specialist training and equipment (Roggio et al., 2021; van der Kruk & Reijne, 2018). To many users, this level of technology in not an option. To combat this, more affordable, accessible, and simpler methods are adopted (Adesida et al., 2019). However, the level of detail can be sacrificed, as well as the quantity of data collected (Adesida et al., 2019; Armitano-Lago et al., 2022; Frevel et al., 2022). E-textiles offer a similar level of detail within the data to that of the gold-standard, whilst costing a fraction of the price (Adesida et al., 2019; Gonçalves et al., 2018). Furthermore, e-textiles are often simple to use and are designed with the user in mind, to help achieve the specific objectives of training (Adesida et al., 2019; Tajadura-Jiménez et al., 2020).

KiTT offers a new perspective of sport technology, with the main attraction being that the user only must wear the garment before collecting data of any sort. This allows the user to perform the movement with little/no changes in their mechanics, as there are not multiple markers, devices, and cables attached which is the case for alternative technological solutions (Luczak et al., 2019; Myer et al., 2014; van der Kruk & Reijne, 2018). When performing a squatting motion on two-dimensional motion capture, results are still highly valid and accurate when compared to a 3D motion capture system, displaying similar results to KiTT from the current study (Herrington et al., 2017). As two-dimensional motion capture requires users to wear reflective markers, there is currently a greater range of variables that can be captured away from the knee, that concern the trunk and the hip (Bazett-Jones et al., 2022; Herrington et al., 2017). However, if the primary aim of a user's session involves the measuring of the RKA, whether that be for velocity-based training, or rehabilitative measures, KiTT provides a valid and reliable reading when performing a squatting motion.

5. Concluding Remarks

The research project collectively identified a need and desire from end-users for more sport technology, such that can capture relative knee angle as well as additional kinematic variables. By creating dialogue with end-users and applied practitioners, additional data that was outside of the scope of questioning was collected, which demonstrated 91% of coaches currently utilising technology within their work, with 70% working on a restricted time frame. By having access to more user-friendly and portable data collection devices, end-users will be able to meet their objectives and continue to work efficiently (Adesida et al., 2019; Luczak et al., 2019). Whilst the research project emphasised the need for such technology from coaches, there is scope for future research into the players and ultimate end-users viewpoints on the technology as ultimately they will be the individuals wearing the technology.

In addition to this, KiTT can accurately and reliably capture relative knee angle in comparison to Vicon across five commonly used sporting exercises. As well as this, the data gathered is valid and representative of the motion being carried out. To confidently state that KiTT can be used within future work, there needs to be additional research that solidifies the use of the inertial measurement unit in calculating a relative knee angle, as well as additional sporting variables. Future development into the technology may aid the data collected, with advancements in the sample rate, and possible removal/fix of the 'dead-zone'. By remediating these issues, KiTT can truly serve as an alternative to current technological systems, which is more portable, cost-friendly, simple to use, and therefore more accessible to the coaches that require this type of kit.

The current study aimed to address the reliability and validity of a new e-textile that can capture RKA with results comparable to that of the current gold-standard criterion methods. The results identified that KiTT has similar results to that of Vicon, across five commonly adopted sporting exercises, whilst demonstrating high to very-high levels of reliability and validity (Koo & Li, 2016; Mukaka, 2012). Although the sporting exercises are commonly used within practical settings, four of the movements involve a squatting movement pattern, with many more sporting exercises that were not included within the study incorporating alternative movement patterns (i.e., deadlifts, leg extension, and more sport-specific movements) (Cannell et al., 2001; Martín-Fuentes et al., 2020). The results from the current study highlight the accuracy of KiTT when compared to gold-standard methods, however this is a result of direct input from a more advanced system. Future studies should aim to include more spirting exercises (e.g., leg extension, lateral hops, and deadlift variations) to further investigate the reliability and validity of KiTT, and to explore the true limitations of the technology. Additionally, to solidify KiTT's position within the strength and conditioning environment, there needs to be internal development into true angle calculation from the sensor, inertial measurement unit, and appropriate algorithms.

6. Bibliography

Adesida, Y., Papi, E., & McGregor, A. H. (2019). Exploring the Role of Wearable Technology in Sport Kinematics and Kinetics: A Systematic Review. *Sensors (Basel)*, *19*(7). https://doi.org/10.3390/s19071597

Albasini, A., Krause, M., & Rembitzki, I. V. (2010). *Using whole body vibration in physical therapy and sport E-Book: Clinical practice and treatment exercises*. Elsevier Health Sciences.

Amitrano, F., Coccia, A., Ricciardi, C., Donisi, L., Cesarelli, G., Capodaglio, E. M., & D'Addio, G. (2020). Design and Validation of an E-Textile-Based Wearable Sock for Remote Gait and Postural Assessment. *Sensors (Basel, Switzerland)*, *20*(22), 6691. https://doi.org/10.3390/s20226691

Ancillao, A., Aertbeliën, E., & De Schutter, J. (2021). Effect of the soft tissue artifact on marker measurements and on the calculation of the helical axis of the knee during a gait cycle: A study on the CAMS-Knee data set. *Human Movement Science*, *80*, 102866. https://doi.org/https://doi.org/10.1016/j.humov.2021.102866

Armitano-Lago, C., Willoughby, D., & Kiefer, A. W. (2022). A SWOT Analysis of Portable and Low-Cost Markerless Motion Capture Systems to Assess Lower-Limb Musculoskeletal Kinematics in Sport [Review]. *Frontiers in Sports and Active Living*, *3*. https://doi.org/10.3389/fspor.2021.809898

Aroganam, G., Manivannan, N., & Harrison, D. (2019). Review on Wearable Technology Sensors Used in Consumer Sport Applications. *Sensors*, *19*, 1983. https://doi.org/10.3390/s19091983

Auepanwiriyakul, C., Waibel, S., Songa, J., Bentley, P., & Faisal, A. A. (2020). Accuracy and Acceptability of Wearable Motion Tracking for Inpatient Monitoring Using Smartwatches. *Sensors*, *20*(24).

Bal, B. S., & Dureja, G. (2012). Hawk Eye: A Logical Innovative Technology Use in Sports for Effective Decision Making.

Bazett-Jones, D. M., Waiteman, M. C., & Glaviano, N. R. (2022). Depth of single-leg squat influences the two-dimensional analysis of knee, hip, and pelvis frontal plane motion in pain-free women. *Gait & Posture*, *98*, 279-282. https://doi.org/https://doi.org/10.1016/j.gaitpost.2022.10.001

Beckham, G., Suchomel, T., & Mizuguchi, S. (2014). Force Plate Use in Performance Monitoring and Sport Science Testing. *New Studies in Athletics*, *29*, 25-37.

Bell, K., Fahmy, E., & Gordon, D. (2016). Quantitative conversations: the importance of developing rapport in standardised interviewing. *Quality & Quantity*, *50*(1), 193-212. https://doi.org/10.1007/s11135-014-0144-2

Bermon, S., Garrandes, F., Szabo, A., Berkovics, I., & Adami, P. E. (2021). Effect of Advanced Shoe Technology on the Evolution of Road Race Times in Male and Female Elite Runners [Original Research]. *Frontiers in Sports and Active Living*, *3*. https://doi.org/10.3389/fspor.2021.653173

Bland, J. M., & Altman, D. G. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *Lancet*, *1*(8476), 307-310.

Bouzigon, R., Dupuy, O., Tiemessen, I., De Nardi, M., Bernard, J. P., Mihailovic, T., Theurot, D., Miller, E. D., Lombardi, G., & Dugué, B. M. (2021). Cryostimulation for Post-exercise Recovery in Athletes: A Consensus and Position Paper. *Front Sports Act Living*, *3*, 688828. https://doi.org/10.3389/fspor.2021.688828

Bragaru, M., Dekker, R., & Geertzen, J. H. B. (2012). Sport prostheses and prosthetic adaptations for the upper and lower limb amputees: an overview of peer reviewed literature. *Prosthetics and Orthotics International*, *36*(3), 290-296. https://doi.org/10.1177/0309364612447093

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77-101. https://doi.org/10.1191/1478088706qp063oa

Brendgen, R., Nolden, R., Simon, J., Junge, T., Zöll, K., & Schwarz-Pfeiffer, A. (2022). Textile Strain Sensor Enhancement by Coating Metal Yarns with Carbon-Filled Silicone. *Polymers (Basel)*, *14*(13). https://doi.org/10.3390/polym14132525

Cabarkapa, D., Fry, A. C., Cabarkapa, D. V., Myers, C. A., Jones, G. T., & Deane, M. A. (2022). Kinetic and Kinematic Characteristics of Proficient and Non-Proficient 2-Point and 3-Point Basketball Shooters. *Sports*, *10*(1), 2. https://www.mdpi.com/2075-4663/10/1/2

Cannell, L. J., Taunton, J. E., Clement, D. B., Smith, C., & Khan, K. M. (2001). A randomised clinical trial of the efficacy of drop squats or leg extension/leg curl exercises to treat clinically diagnosed jumper's knee in athletes: pilot study. *British Journal of Sports Medicine*, *35*(1), 60. https://doi.org/10.1136/bjsm.35.1.60

Carlin, A., Murphy, M. H., & Gallagher, A. M. (2015). Current influences and approaches to promote future physical activity in 11–13 year olds: a focus group study. *BMC Public Health*, *15*(1), 1270. https://doi.org/10.1186/s12889-015-2601-9

Cesarelli, G., Donisi, L., Coccia, A., Amitrano, F., D'Addio, G., & Ricciardi, C. (2021). The E-Textile for Biomedical Applications: A Systematic Review of Literature. *Diagnostics (Basel)*, *11*(12). https://doi.org/10.3390/diagnostics11122263

Chandrasekaran, R., Katthula, V., & Moustakas, E. (2020). Patterns of Use and Key Predictors for the Use of Wearable Health Care Devices by US Adults: Insights from a National Survey. *J Med Internet Res*, *22*(10), e22443. https://doi.org/10.2196/22443

Chen, D. (2022). Image Recognition of Sports Athletes' High-Intensity Sports Injuries Based on Binocular Stereo Vision. *Comput Intell Neurosci*, *2022*, 4322597. https://doi.org/10.1155/2022/4322597

Chen, H., Rogalski, M. M., & Anker, J. N. (2012). Advances in functional X-ray imaging techniques and contrast agents. *Phys Chem Chem Phys*, *14*(39), 13469-13486. https://doi.org/10.1039/c2cp41858d

Cheng, R., & H M Bergmann, J. (2022). Impact and workload are dominating on-field data monitoring techniques to track health and well-being of team-sports athletes. *Physiological Measurement*, *43*(3), 03TR01. https://doi.org/10.1088/1361-6579/ac59db

Choo, C. Z. Y., Chow, J. Y., & Komar, J. (2022). Validation of the Perception Neuron system for full-body motion capture. *PLOS ONE*, *17*(1), e0262730. https://doi.org/10.1371/journal.pone.0262730

Cloosterman, K. L. A., Fokkema, T., de Vos, R. J., van Oeveren, B., Bierma-Zeinstra, S. M. A., & van Middelkoop, M. (2022). Feasibility and usability of GPS data in exploring associations between training load and running-related knee injuries in recreational runners. *BMC Sports Sci Med Rehabil*, *14*(1), 78. https://doi.org/10.1186/s13102-022-00472-8

Collins, H., & Evans, R. (2012). Sport-decision aids and the "CSI-effect": Why cricket uses Hawk-Eye well and tennis uses it badly. *Public understanding of science (Bristol, England)*, *21*, 904-921. https://doi.org/10.1177/0963662511407991

Cosoli, G., Antognoli, L., Veroli, V., & Scalise, L. (2022). Accuracy and Precision of Wearable Devices for Real-Time Monitoring of Swimming Athletes. *Sensors (Basel)*, *22*(13). https://doi.org/10.3390/s22134726

Cotter, J. A., Chaudhari, A. M., Jamison, S. T., & Devor, S. T. (2013). Knee joint kinetics in relation to commonly prescribed squat loads and depths. *J Strength Cond Res*, *27*(7), 1765-1774. https://doi.org/10.1519/JSC.0b013e3182773319

Crema, M. D., Yamada, A. F., Guermazi, A., Roemer, F. W., & Skaf, A. Y. (2015). Imaging techniques for muscle injury in sports medicine and clinical relevance. *Curr Rev Musculoskelet Med*, *8*(2), 154-161. https://doi.org/10.1007/s12178-015-9260-4

de Almeida, T. F., Morya, E., Rodrigues, A. C., & de Azevedo Dantas, A. F. O. (2021). Development of a Low-Cost Open-Source Measurement System for Joint Angle Estimation. *Sensors (Basel)*, *21*(19). https://doi.org/10.3390/s21196477

DeJonckheere, M., & Vaughn, L. M. (2019). Semistructured interviewing in primary care research: a balance of relationship and rigour. *Family Medicine and Community Health*, *7*(2), e000057. https://doi.org/10.1136/fmch-2018-000057

Diaz, K. M., Krupka, D. J., Chang, M. J., Peacock, J., Ma, Y., Goldsmith, J., Schwartz, J. E., & Davidson, K. W. (2015). Fitbit®: An accurate and reliable device for wireless physical activity tracking. *Int J Cardiol*, *185*, 138-140. https://doi.org/10.1016/j.ijcard.2015.03.038

Dickerson, L. C., Peebles, A. T., Moskal, J. T., Miller, T. K., & Queen, R. M. (2020). Physical Performance Improves With Time and a Functional Knee Brace in Athletes After ACL Reconstruction. *Orthopaedic journal of sports medicine*, *8*(8), 2325967120944255. https://doi.org/10.1177/2325967120944255

Dingwell, J. B., & Davis, B. L. (1996). A rehabilitation treadmill with software for providing real-time gait analysis and visual feedback. *J Biomech Eng*, *118*(2), 253-255. https://doi.org/10.1115/1.2795968

Dobkin, B. H. (2013). Wearable motion sensors to continuously measure real-world physical activities. *Curr Opin Neurol*, *26*(6), 602-608. https://doi.org/10.1097/wco.0000000000000026

Dong, M., Yao, G., Li, J., & Zhang, L. (2020). Calibration of Low Cost IMU's Inertial Sensors for Improved Attitude Estimation. *Journal of Intelligent & Robotic Systems*, *100*(3), 1015-1029. https://doi.org/10.1007/s10846-020-01259-0

Drenowatz, C., & Eisenmann, J. C. (2011). Validation of the SenseWear Armband at high intensity exercise. *Eur J Appl Physiol*, *111*(5), 883-887. https://doi.org/10.1007/s00421-010-1695-0

Düking, P., Hotho, A., Holmberg, H. C., Fuss, F. K., & Sperlich, B. (2016). Comparison of Non-Invasive Individual Monitoring of the Training and Health of Athletes with Commercially Available Wearable Technologies. *Frontiers in physiology*, *7*, 71. https://doi.org/10.3389/fphys.2016.00071

Dyer, B. (2015). The controversy of sports technology: a systematic review. *SpringerPlus*, *4*, 524. https://doi.org/10.1186/s40064-015-1331-x

Ebben, W. P., Hintz, M. J., & Simenz, C. J. (2005). Strength and conditioning practices of Major League Baseball strength and conditioning coaches. *J Strength Cond Res*, *19*(3), 538-546. https://doi.org/10.1519/r-15464.1

Edmison, J., Jones, M., Lockhart, T., & Martin, T. (2004). An e-textile system for motion analysis. *Stud Health Technol Inform*, *108*, 292-301.

Elliot, C. A., Hamlin, M. J., & Lizamore, C. A. (2019). Validity and Reliability of the Hexoskin Wearable Biometric Vest During Maximal Aerobic Power Testing in Elite Cyclists. *The Journal of Strength & Conditioning Research*, *33*(5), 1437-1444. https://doi.org/10.1519/jsc.0000000000002005

Ellison, P. H., Kearney, P. E., Sparks, S. A., Murphy, P. N., & Marchant, D. C. (2017). Further evidence against eye–hand coordination as a general ability. *International Journal of Sports Science & Coaching*, *13*(5), 687-693. https://doi.org/10.1177/1747954117747132

Endo, Y., Miura, M., & Sakamoto, M. (2020). The relationship between the deep squat movement and the hip, knee and ankle range of motion and muscle strength. *J Phys Ther Sci*, *32*(6), 391-394. https://doi.org/10.1589/jpts.32.391

Evans, A. B., Barker-Ruchti, N., Blackwell, J., Clay, G., Dowling, F., Frydendal, S., Gliemann Hybholt, M., Hausken-Sutter, S. E., Lenneis, V., Malcolm, D., Phoenix, C., Smith, B., Svendler Nielsen, C., Wilcock, L., Williams, O., & Winther, H. (2021). Qualitative research in sports studies: challenges, possibilities and the current state of play. *European Journal for Sport and Society*, *18*(1), 1-17. https://doi.org/10.1080/16138171.2021.1899969

Faghy, M. A., & Brown, P. I. (2014). Preloaded Time Trial to Assess Load Carriage Performance. *The Journal of Strength & Conditioning Research*, *28*(12), 3354-3362. https://doi.org/10.1519/jsc.0000000000000555

Fernandez-Fernandez, J., Ulbricht, A., & Ferrauti, A. (2014). Fitness testing of tennis players: How valuable is it? *British Journal of Sports Medicine*, *48*(Suppl 1), i22. https://doi.org/10.1136/bjsports-2013-093152

Ferreira, A. G., Fernandes, D., Branco, S., Monteiro, J. L., Cabral, J., Catarino, A. P., & Rocha, A. M. (2016, 14-17 March 2016). A smart wearable system for sudden infant death syndrome monitoring. 2016 IEEE International Conference on Industrial Technology (ICIT),

Finkelstein, E. A., Haaland, B. A., Bilger, M., Sahasranaman, A., Sloan, R. A., Nang, E. E. K., & Evenson, K. R. (2016). Effectiveness of activity trackers with and without incentives to increase physical activity (TRIPPA): a randomised controlled trial. *Lancet Diabetes Endocrinol*, *4*(12), 983-995. https://doi.org/10.1016/s2213-8587(16)30284-4

Finnoff, J. T., Ray, J., Corrado, G., Kerkhof, D., & Hill, J. (2016). Sports Ultrasound: Applications Beyond the Musculoskeletal System. *Sports health*, *8*(5), 412-417. https://doi.org/10.1177/1941738116664041

Firek, W., Płoszaj, K., & Czechowski, M. (2020). Pedagogical Function of Referees in Youth Sport: Assessment of the Quality of Referee-Player Interactions in Youth Soccer. *International journal of environmental research and public health*, *17*(3). https://doi.org/10.3390/ijerph17030905

Frevel, N., Beiderbeck, D., & Schmidt, S. L. (2022). The impact of technology on sports – A prospective study. *Technological Forecasting and Social Change*, *182*, 121838. https://doi.org/https://doi.org/10.1016/j.techfore.2022.121838

Gamble, P., Chia, L., & Allen, S. (2020). The illogic of being data-driven: reasserting control and restoring balance in our relationship with data and technology in football. *Science and Medicine in Football*, *4*. https://doi.org/10.1080/24733938.2020.1854842

Gao, Z., & Lee, J. E. (2019). Emerging Technology in Promoting Physical Activity and Health: Challenges and Opportunities. *Journal of clinical medicine*, *8*(11), 1830. https://doi.org/10.3390/jcm8111830

Gathercole, R., Sporer, B., Stellingwerff, T., & Sleivert, G. (2015). Alternative countermovement-jump analysis to quantify acute neuromuscular fatigue. *Int J Sports Physiol Perform*, *10*(1), 84-92. https://doi.org/10.1123/ijspp.2013-0413

Ghaida, H. A., Mottet, S., & Goujon, J. M. (2014, 26-30 Aug. 2014). A real time study of the human equilibrium using an instrumented insole with 3 pressure sensors.

2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society,

Gierczuk, D., & Bujak, Z. (2014). Reliability and Accuracy of Batak Lite Tests Used for Assessing Coordination Motor Abilities in Wrestlers. *Polish Journal of Sport and Tourism*, *21*. https://doi.org/10.2478/pjst-2014-0007

Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Methods of data collection in qualitative research: interviews and focus groups. *British Dental Journal*, *204*(6), 291-295. https://doi.org/10.1038/bdj.2008.192

Gomez-Ruano, M.-A., Ibáñez, S. J., & Leicht, A. S. (2020). Editorial: Performance Analysis in Sport [Editorial]. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.611634

Gonçalves, C., Ferreira da Silva, A., Gomes, J., & Simoes, R. (2018). Wearable E-Textile Technologies: A Review on Sensors, Actuators and Control Elements. *Inventions*, *3*(1).

Goncu-Berk, G., & Tuna, B. G. (2021). The Effect of Sleeve Pattern and Fit on E-Textile Electromyography (EMG) Electrode Performance in Smart Clothing Design. *Sensors*, *21*(16).

Gong, Z., Xiang, Z., OuYang, X., Zhang, J., Lau, N., Zhou, J., & Chan, C. C. (2019). Wearable Fiber Optic Technology Based on Smart Textile: A Review. *Materials (Basel)*, *12*(20). https://doi.org/10.3390/ma12203311

Haddad, M., Hermassi, S., Aganovic, Z., Dalansi, F., Kharbach, M., Mohamed, A. O., & Bibi, K. W. (2020). Ecological Validation and Reliability of Hexoskin Wearable

Body Metrics Tool in Measuring Pre-exercise and Peak Heart Rate During Shuttle Run Test in Professional Handball Players. *Frontiers in physiology*, *11*, 957. https://doi.org/10.3389/fphys.2020.00957

Halson, S. L. (2014). Monitoring training load to understand fatigue in athletes. *Sports medicine (Auckland, N.Z.)*, *44 Suppl 2*(Suppl 2), S139-S147. https://doi.org/10.1007/s40279-014-0253-z

Harito, C., Utari, L., Putra, B. R., Yuliarto, B., Purwanto, S., Zaidi, S. Z. J., Bavykin, D. V., Marken, F., & Walsh, F. C. (2020). Review—The Development of Wearable Polymer-Based Sensors: Perspectives. *Journal of The Electrochemical Society*, *167*(3), 037566. https://doi.org/10.1149/1945-7111/ab697c

Harris, N. K., Cronin, J., Taylor, K.-L., Boris, J., & Sheppard, J. (2010). Understanding Position Transducer Technology for Strength and Conditioning Practitioners. *Strength & Conditioning Journal*, *32*(4). https://journals.lww.com/nsca-scj/Fulltext/2010/08000/Understanding_Position_Transducer_Technology_for.7.aspx

Hébert-Losier, K., & Pamment, M. (2023). Advancements in running shoe technology and their effects on running economy and performance – a current concepts overview. *Sports Biomechanics*, *22*(3), 335-350. https://doi.org/10.1080/14763141.2022.2110512

Hedt, C., McCulloch, P. C., Harris, J. D., & Lambert, B. S. (2022). Blood Flow Restriction Enhances Rehabilitation and Return to Sport: The Paradox of Proximal Performance. *Arthrosc Sports Med Rehabil*, *4*(1), e51-e63. https://doi.org/10.1016/j.asmr.2021.09.024

Herrington, L., Alenezi, F., Alzhrani, M., Alrayani, H., & Jones, R. (2017). The reliability and criterion validity of 2D video assessment of single leg squat and hop landing. *Journal of Electromyography and Kinesiology*, *34*, 80-85. https://doi.org/https://doi.org/10.1016/j.jelekin.2017.04.004

Hoeber, L., & Shaw, S. (2017). Contemporary qualitative research methods in sport management. *Sport Management Review*, *20*(1), 4-7. https://doi.org/https://doi.org/10.1016/j.smr.2016.11.005

Holder, U., Ehrmann, T., & König, A. (2022). Monitoring experts: insights from the introduction of video assistant referee (VAR) in elite football. *Journal of Business Economics*, *92*(2), 285-308. https://doi.org/10.1007/s11573-021-01058-5

Hutchinson, H. (2008, 2008/04//). Beyond the shark skin suit: faster designs and deeper analysis advance the high-tech sport of swimming. *Mechanical Engineering-CIME*, *130*(4), 42+. https://link.gale.com/apps/doc/A177550701/AONE?u=googlescholar&sid=bookmark-AONE&xid=49f15895

Isaia, C., McMaster, S. A., & McNally, D. (2020). Study of Performance of Knitted Conductive Sleeves as Wearable Textile Strain Sensors for Joint Motion Tracking. *Annu Int Conf IEEE Eng Med Biol Soc*, *2020*, 4555-4558. https://doi.org/10.1109/embc44109.2020.9176429

Isaia, C., McNally, D. S., McMaster, S. A., & Branson, D. T. (2018). Effect of mechanical preconditioning on the electrical properties of knitted conductive textiles during cyclic loading. *Textile Research Journal*, *89*(3), 445-460. https://doi.org/10.1177/0040517517748496

Ismar, E., Kurşun Bahadir, S., Kalaoglu, F., & Koncar, V. (2020). Futuristic Clothes: Electronic Textiles and Wearable Technologies. *Glob Chall*, *4*(7), 1900092. https://doi.org/10.1002/gch2.201900092

Issatayeva, A., Beisenova, A., Tosi, D., & Molardi, C. (2020). Fiber-Optic Based Smart Textiles for Real-Time Monitoring of Breathing Rate. *Sensors (Basel)*, *20*(12). https://doi.org/10.3390/s20123408

Ito, T., Noritake, K., Ito, Y., Tomita, H., Mizusawa, J., Sugiura, H., Matsunaga, N., Ochi, N., & Sugiura, H. (2022). Three-dimensional gait analysis of lower extremity gait parameters in Japanese children aged 6 to 12 years. *Sci Rep*, *12*(1), 7822. https://doi.org/10.1038/s41598-022-11906-1

Jamshed, S. (2014). Qualitative research method-interviewing and observation. *Journal of basic and clinical pharmacy*, *5*(4), 87-88. https://doi.org/10.4103/0976-0105.141942

Jansen, K. M. B. (2020). Performance Evaluation of Knitted and Stitched Textile Strain Sensors. *Sensors (Basel, Switzerland)*, *20*(24), 7236. https://doi.org/10.3390/s20247236

Januskevica, A., Semjonova, G., Oks, A., Katashev, A., & Eizentals, P. (2020). Evaluation of the Foot Performance in" Single Leg Squat" Test of Female Athletes using Smart Socks. icSPORTS,

Jayasinghe, U., Harwin, W. S., & Hwang, F. (2019). Comparing Clothing-Mounted Sensors with Wearable Sensors for Movement Analysis and Activity Classification. *Sensors (Basel)*, *20*(1). https://doi.org/10.3390/s20010082

Jin, H., Nayeem, M. O. G., Lee, S., Matsuhisa, N., Inoue, D., Yokota, T., Hashizume, D., & Someya, T. (2019). Highly Durable Nanofiber-Reinforced Elastic Conductors for Skin-Tight Electronic Textiles. *ACS Nano*, *13*(7), 7905-7912. https://doi.org/10.1021/acsnano.9b02297

Jones, R. L., & Wallace, M. (2005). Another bad day at the training ground: Coping with ambiguity in the coaching context. *Sport, Education and Society*, *10*(1), 119-134. https://doi.org/10.1080/1357332052000308792

Ketola, R., Mishra, V., & Kiourti, A. (2020). Modeling Fabric Movement for Future E-Textile Sensors. *Sensors*, *20*(13).

Koo, T. K., & Li, M. Y. (2016). A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. *J Chiropr Med*, *15*(2), 155-163. https://doi.org/10.1016/j.jcm.2016.02.012

Kozinc, Ž., Žitnik, J., Smajla, D., & Šarabon, N. (2022). The difference between squat jump and countermovement jump in 770 male and female participants from different sports. *European Journal of Sport Science*, *22*(7), 985-993. https://doi.org/10.1080/17461391.2021.1936654

Kraemer, W., Denegar, C., & Flanagan, S. (2009). Recovery from injury in sport: considerations in the transition from medical care to performance care. *Sports health*, *1*(5), 392-395. https://doi.org/10.1177/1941738109343156

Krenn, P. J., Titze, S., Oja, P., Jones, A., & Ogilvie, D. (2011). Use of global positioning systems to study physical activity and the environment: a systematic review. *Am J Prev Med*, *41*(5), 508-515. https://doi.org/10.1016/j.amepre.2011.06.046

Lago-Peñas, C., Gómez, M. A., & Pollard, R. (2020). The effect of the Video Assistant Referee on referee's decisions in the Spanish LaLiga. *International Journal of Sports Science & Coaching*, *16*(3), 824-829. https://doi.org/10.1177/1747954120980111

Lees, A. (2019). The evolution of racket sport science—a personal reflection. *German Journal of Exercise and Sport Research*, *49*(3), 213-220. https://doi.org/10.1007/s12662-019-00604-2

Li, M., Torah, R., Nunes-Matos, H., Wei, Y., Beeby, S., Tudor, J., & Yang, K. (2020). Integration and Testing of a Three-Axis Accelerometer in a Woven E-Textile Sleeve for Wearable Movement Monitoring. *Sensors (Basel)*, *20*(18). https://doi.org/10.3390/s20185033

Li, R. T., Kling, S. R., Salata, M. J., Cupp, S. A., Sheehan, J., & Voos, J. E. (2016). Wearable Performance Devices in Sports Medicine. *Sports health*, *8*(1), 74-78. https://doi.org/10.1177/1941738115616917

Li, Y., Miao, X., Niu, L., Jiang, G., & Ma, P. (2019). Human Motion Recognition of Knitted Flexible Sensor in Walking Cycle. *Sensors (Basel, Switzerland)*, *20*(1), 35. https://doi.org/10.3390/s20010035

Liang, M., Zhao, N., & Li, Y. (2022). Nine-Axis Sensor for Athlete Physical Training Load Characteristics. *Contrast Media Mol Imaging*, *2022*, 1538331. https://doi.org/10.1155/2022/1538331

Lin, S., Song, Y., Cen, X., Bálint, K., Fekete, G., & Sun, D. (2022). The Implications of Sports Biomechanics Studies on the Research and Development of Running Shoes: A

Systematic Review. *Bioengineering (Basel)*, *9*(10). https://doi.org/10.3390/bioengineering9100497

Liu, R., Wang, S., & Lao, T. T. (2012). A Novel Solution of Monitoring Incontinence Status by Conductive Yarn and Advanced Seamless Knitting Techniques. *Journal of Engineered Fibers and Fabrics*, *7*(4), 155892501200700415. https://doi.org/10.1177/155892501200700415

Liu, X., Su, X., Tamminen, S., Korhonen, T., & Röning, J. (2019, 5-7 June 2019). Predicting the Heart Rate Response to Outdoor Running Exercise. 2019 IEEE 32nd International Symposium on Computer-Based Medical Systems (CBMS),

Lombardi, G., Ziemann, E., & Banfi, G. (2017). Whole-Body Cryotherapy in Athletes: From Therapy to Stimulation. An Updated Review of the Literature. *Frontiers in physiology*, *8*, 258. https://doi.org/10.3389/fphys.2017.00258

López, G., Custodio, V., & Moreno, J. I. (2010). LOBIN: E-textile and wireless-sensor-network-based platform for healthcare monitoring in future hospital environments. *IEEE Trans Inf Technol Biomed*, *14*(6), 1446-1458. https://doi.org/10.1109/titb.2010.2058812

Luczak, T., Burch, R., Lewis, E., Chander, H., & Ball, J. (2019). State-of-the-art review of athletic wearable technology: What 113 strength and conditioning coaches and athletic trainers from the USA said about technology in sports. *International Journal of Sports Science & Coaching*, *15*(1), 26-40. https://doi.org/10.1177/1747954119885244

Mackenzie, R., & Cushion, C. (2012). Performance analysis in football: A critical review and implications for future research. *Journal of sports sciences*, *31*. https://doi.org/10.1080/02640414.2012.746720

Mali, N., & Kumar Dey, S. (2020). Modern technology and sports performance: An overview. *5*, 212-216.

Malone, J. J., Lovell, R., Varley, M. C., & Coutts, A. J. (2017). Unpacking the Black Box: Applications and Considerations for Using GPS Devices in Sport. *Int J Sports Physiol Perform*, *12*(Suppl 2), S218-s226. https://doi.org/10.1123/ijspp.2016-0236

Marks, L. J., & Michael, J. W. (2001). Science, medicine, and the future: Artificial limbs. *BMJ*, *323*(7315), 732-735. https://doi.org/10.1136/bmj.323.7315.732

Martín-Fuentes, I., Oliva-Lozano, J. M., & Muyor, J. M. (2020). Evaluation of the Lower Limb Muscles' Electromyographic Activity during the Leg Press Exercise and Its Variants: A Systematic Review. *International journal of environmental research and public health*, *17*(13). https://doi.org/10.3390/ijerph17134626

Mayne, R. S., Bleakley, C. M., & Matthews, M. (2021). Use of monitoring technology and injury incidence among recreational runners: a cross-sectional study. *BMC Sports Science, Medicine and Rehabilitation*, *13*(1), 116. https://doi.org/10.1186/s13102-021-00347-4

McKenzie, J. E., & Osgood, D. W. (2004). Validation of a new telemetric core temperature monitor. *Journal of Thermal Biology*, *29*(7), 605-611. https://doi.org/https://doi.org/10.1016/j.jtherbio.2004.08.020

Meena, J. S., Choi, S. B., Jung, S.-B., & Kim, J.-W. (2023). Electronic textiles: New age of wearable technology for healthcare and fitness solutions. *Materials Today Bio*, *19*, 100565. https://doi.org/https://doi.org/10.1016/j.mtbio.2023.100565

Mishra, V., & Kiourti, A. (2019). Wrap-Around Wearable Coils for Seamless Monitoring of Joint Flexion. *IEEE Transactions on Biomedical Engineering*, *66*(10), 2753-2760. https://doi.org/10.1109/TBME.2019.2895293

Montes, J., Young, J. C., Tandy, R., & Navalta, J. W. (2018). Reliability and Validation of the Hexoskin Wearable Bio-Collection Device During Walking Conditions. *International journal of exercise science*, *11*(7), 806-816.

Morales, A. T., Tamayo Fajardo, J. A., & González-García, H. (2019). High-Speed Swimsuits and Their Historical Development in Competitive Swimming. *Front Psychol*, *10*, 2639. https://doi.org/10.3389/fpsyg.2019.02639

Mortaza, N., Ebrahimi, I., Jamshidi, A. A., Abdollah, V., Kamali, M., Abas, W. A. B. W., & Osman, N. A. A. (2012). The Effects of a Prophylactic Knee Brace and Two Neoprene Knee Sleeves on the Performance of Healthy Athletes: A Crossover Randomized Controlled Trial. *PLOS ONE*, *7*(11), e50110. https://doi.org/10.1371/journal.pone.0050110

Mukaka, M. M. (2012). Statistics corner: A guide to appropriate use of correlation coefficient in medical research. *Malawi Med J*, *24*(3), 69-71.

Muniz-Pardos, B., Sutehall, S., Angeloudis, K., Shurlock, J., & Pitsiladis, Y. P. (2019). The Use of Technology to Protect the Health of Athletes During Sporting Competitions in the Heat. *Frontiers in Sports and Active Living*, *1*, 38-38. https://doi.org/10.3389/fspor.2019.00038

Myer, G. D., Kushner, A. M., Brent, J. L., Schoenfeld, B. J., Hugentobler, J., Lloyd, R. S., Vermeil, A., Chu, D. A., Harbin, J., & McGill, S. M. (2014). The back squat: A proposed assessment of functional deficits and technical factors that limit performance. *Strength and conditioning journal*, *36*(6), 4-27. https://doi.org/10.1519/SSC.0000000000000103

Nakata, H., Nagami, T., Higuchi, T., Sakamoto, K., & Kanosue, K. (2013). Relationship between performance variables and baseball ability in youth baseball players. *J Strength Cond Res*, *27*(10), 2887-2897. https://doi.org/10.1519/JSC.0b013e3182a1f58a

Nelson, B. W., & Allen, N. B. (2019). Accuracy of Consumer Wearable Heart Rate Measurement During an Ecologically Valid 24-Hour Period: Intraindividual Validation Study. *JMIR mHealth and uHealth*, *7*(3), e10828. https://doi.org/10.2196/10828

Nguyen, L., Rodríguez-Martín, D., Català, A., Pérez, C., Samà Monsonís, A., & Cavallaro, A. (2015). *Basketball Activity Recognition using Wearable Inertial Measurement Units*. https://doi.org/10.1145/2829875.2829930

Nibbeling, N., Simons, M., Sporrel, K., & Deutekom, M. (2021). A Focus Group Study Among Inactive Adults Regarding the Perceptions of a Theory-Based Physical Activity App [Original Research]. *Frontiers in Public Health*, *9*. https://doi.org/10.3389/fpubh.2021.528388

Nyumba, T., Wilson, K., Derrick, C. J., & Mukherjee, N. (2018). The use of focus group discussion methodology: Insights from two decades of application in conservation. *Methods in Ecology and Evolution*, *9*(1), 20-32. https://doi.org/https://doi.org/10.1111/2041-210X.12860

O'Donnell, S., Tavares, F., McMaster, D., Chambers, S., & Driller, M. (2017). The validity and reliability of the GymAware linear position transducer for measuring counter-movement jump performance in female athletes. *Measurement in Physical Education and Exercise Science*. https://doi.org/10.1080/1091367X.2017.1399892

Oks, A., Katashev, A., Eizentals, P., Rozenstoka, S., & Suna, D. (2020). Smart socks: new effective method of gait monitoring for systems with limited number of plantar sensors. *Health and Technology*, *10*(4), 853-860. https://doi.org/10.1007/s12553-020-00421-w

Ometov, A., Shubina, V., Klus, L., Skibińska, J., Saafi, S., Pascacio, P., Flueratoru, L., Gaibor, D. Q., Chukhno, N., Chukhno, O., Ali, A., Channa, A., Svertoka, E., Qaim, W. B., Casanova-Marqués, R., Holcer, S., Torres-Sospedra, J., Casteleyn, S., Ruggeri, G., . . . Lohan, E. S. (2021). A Survey on Wearable Technology: History, State-of-the-Art and Current Challenges. *Computer Networks*, *193*, 108074. https://doi.org/https://doi.org/10.1016/j.comnet.2021.108074

Omoregie, P. (2016). *THE IMPACT OF TECHNOLOGY ON SPORT PERFORMANCE*.

Pasadyn, S. R., Soudan, M., Gillinov, M., Houghtaling, P., Phelan, D., Gillinov, N., Bittel, B., & Desai, M. Y. (2019). Accuracy of commercially available heart rate monitors in athletes: a prospective study. *Cardiovascular diagnosis and therapy*, *9*(4), 379-385. https://doi.org/10.21037/cdt.2019.06.05

Patterson, S. M., Udermann, B. E., Doberstein, S. T., & Reineke, D. M. (2008). The effects of cold whirlpool on power, speed, agility, and range of motion. *J Sports Sci Med*, *7*(3), 387-394.

Peake, J. M., Kerr, G., & Sullivan, J. P. (2018). A Critical Review of Consumer Wearables, Mobile Applications, and Equipment for Providing Biofeedback, Monitoring Stress, and Sleep in Physically Active Populations. *Frontiers in physiology*, *9*, 743. https://doi.org/10.3389/fphys.2018.00743

Pedersen, P. M., Laucella, P., Geurin, A., & Kian, E. (2020). *Strategic sport communication*. Human Kinetics Publishers.

Pendergast, D., Mollendorf, J., Cuviello, R., & Termin, B. (2006). Application of theoretical principles to swimsuit drag reduction. *Sports Engineering*, *9*, 65-76. https://doi.org/10.1007/BF02844859

Pinar, S., Kaya, F., Bicer, B., Erzeybek, M. S., & Cotuk, H. B. (2012). Different recovery methods and muscle performance after exhausting exercise: comparison of the effects of electrical muscle stimulation and massage. *Biology of sport*, *29*(4), 269-275. https://doi.org/10.5604/20831862.1019664

Pojskic, H., Pagaduan, J., Uzicanin, E., Separovic, V., Spasic, M., Foretic, N., & Sekulic, D. (2019). Reliability, Validity and Usefulness of a New Response Time Test for Agility-Based Sports: A Simple vs. Complex Motor Task. *J Sports Sci Med*, *18*(4), 623-635.

Politopoulos, N., Tsiatsos, T., Grouios, G., & Ziagkas, E. (2015, 19-20 Nov. 2015). Implementation and evaluation of a game using natural user interfaces in order to improve response time. 2015 International Conference on Interactive Mobile Communication Technologies and Learning (IMCL),

Postolache, O., Viegas, V., Pereira, J. M. D., Vinhas, D., Girão, P. S., & Postolache, G. (2014, 11-12 June 2014). Toward developing a smart wheelchair for user physiological stress and physical activity monitoring. 2014 IEEE International Symposium on Medical Measurements and Applications (MeMeA),

Powell, D., Stuart, S., & Godfrey, A. (2021). Sports related concussion: an emerging era in digital sports technology. *NPJ digital medicine*, *4*(1), 164.

Rapp, A., & Tirabeni, L. (2020). Self-tracking while doing sport: Comfort, motivation, attention and lifestyle of athletes using personal informatics tools. *International Journal of Human-Computer Studies*, *140*, 102434. https://doi.org/https://doi.org/10.1016/j.ijhcs.2020.102434

Ratten, V. (2020). Sport technology: A commentary. *The Journal of High Technology Management Research*, *31*(1), 100383-100383. https://doi.org/10.1016/j.hitech.2020.100383

Ravé, G., Granacher, U., Boullosa, D., Hackney, A. C., & Zouhal, H. (2020). How to Use Global Positioning Systems (GPS) Data to Monitor Training Load in the "Real World" of Elite Soccer. *Frontiers in physiology*, *11*, 944. https://doi.org/10.3389/fphys.2020.00944

Repon, M. R., & Mikučionienė, D. (2021). Progress in Flexible Electronic Textile for Heating Application: A Critical Review. *Materials (Basel)*, *14*(21). https://doi.org/10.3390/ma14216540

Reyes-Bossio, M., Corcuera-Bustamante, S., Veliz-Salinas, G., Villas Boas Junior, M., Delgado-Campusano, M., Brocca-Alvarado, P., Caycho-Rodríguez, T., Casas-Apayco, L., Tutte-Vallarino, V., Carbajal-León, C., & Brandão, R. (2022). Effects of psychological interventions on high sports performance: A systematic review [Systematic Review]. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.1068376

Ride, J., Ringuet, C., Rowlands, D., Lee, J., & James, D. (2013). A Sports Technology Needs Assessment for Performance Monitoring in Swimming. *Procedia Engineering*, *60*, 442-447. https://doi.org/https://doi.org/10.1016/j.proeng.2013.07.072

Rivera, B., Cano, C., Luis, I., & Elias, D. A. (2022). A 3D-Printed Knee Wearable Goniometer with a Mobile-App Interface for Measuring Range of Motion and Monitoring Activities. *Sensors*, *22*(3).

Røe, Y., Rowe, M., Ødegaard, N. B., Sylliaas, H., & Dahl-Michelsen, T. (2019). Learning with technology in physiotherapy education: design, implementation and evaluation of a flipped classroom teaching approach. *BMC Medical Education*, *19*(1), 291. https://doi.org/10.1186/s12909-019-1728-2

Roell, M., Mahler, H., Lienhard, J., Gehring, D., Gollhofer, A., & Roecker, K. (2019). Validation of Wearable Sensors during Team Sport-Specific Movements in Indoor Environments. *Sensors*, *19*(16). https://doi.org/10.3390/s19163458

Roggio, F., Ravalli, S., Maugeri, G., Bianco, A., Palma, A., Di Rosa, M., & Musumeci, G. (2021). Technological advancements in the analysis of human motion and posture management through digital devices. *World J Orthop*, *12*(7), 467-484. https://doi.org/10.5312/wjo.v12.i7.467

Ruckdashel, R. R., Khadse, N., & Park, J. H. (2022). Smart E-Textiles: Overview of Components and Outlook. *Sensors (Basel)*, *22*(16). https://doi.org/10.3390/s22166055

Ruth, J., Willwacher, S., & Korn, O. (2022). Acceptance of Digital Sports: A Study Showing the Rising Acceptance of Digital Health Activities Due to the SARS-CoV-19 Pandemic. *International journal of environmental research and public health*, *19*(1). https://doi.org/10.3390/ijerph19010596

Sallis, J. F., Hovell, M. F., & Richard Hofstetter, C. (1992). Predictors of adoption and maintenance of vigorous physical activity in men and women. *Preventive Medicine*, *21*(2), 237-251. https://doi.org/https://doi.org/10.1016/0091-7435(92)90022-A

Samuel, R. D., Galily, Y., Filho, E., & Tenenbaum, G. (2020). Implementation of the Video Assistant Referee (VAR) as a Career Change-Event: The Israeli Premier League Case Study. *Front Psychol*, *11*, 564855. https://doi.org/10.3389/fpsyg.2020.564855

Sánchez-Medina, L., Pallarés, J., Pérez, C., Morán-Navarro, R., & González-Badillo, J. (2017). Estimation of Relative Load From Bar Velocity in the Full Back Squat Exercise. *Sports Medicine International Open*, *1*, E80-E88. https://doi.org/10.1055/s-0043-102933

Schneider, C., Hanakam, F., Wiewelhove, T., Döweling, A., Kellmann, M., Meyer, T., Pfeiffer, M., & Ferrauti, A. (2018). Heart Rate Monitoring in Team Sports-A

Conceptual Framework for Contextualizing Heart Rate Measures for Training and Recovery Prescription. *Frontiers in physiology*, *9*, 639-639. https://doi.org/10.3389/fphys.2018.00639

Schurr, S. A., Marshall, A. N., Resch, J. E., & Saliba, S. A. (2017). Two-dimensional video analysis is comparable to 3D motion capture in lower extremity movement assessment. *International journal of sports physical therapy*, *12*(2), 163.

Scribbans, T. D., Vecsey, S., Hankinson, P. B., Foster, W. S., & Gurd, B. J. (2016). The Effect of Training Intensity on VO(2)max in Young Healthy Adults: A Meta-Regression and Meta-Analysis. *International journal of exercise science*, *9*(2), 230-247.

Semjonova, G., Davidovica, A., Kozlovskis, N., Okss, A., & Katashevs, A. (2022). Smart Textile Sock System for Athletes' Self-Correction during Functional Tasks: Formative Usability Evaluation. *Sensors (Basel)*, *22*(13). https://doi.org/10.3390/s22134779

Seshadri, D. R., Li, R. T., Voos, J. E., Rowbottom, J. R., Alfes, C. M., Zorman, C. A., & Drummond, C. K. (2019). Wearable sensors for monitoring the internal and external workload of the athlete. *NPJ digital medicine*, *2*, 71-71. https://doi.org/10.1038/s41746-019-0149-2

Seshadri, D. R., Thom, M. L., Harlow, E. R., Gabbett, T. J., Geletka, B. J., Hsu, J. J., Drummond, C. K., Phelan, D. M., & Voos, J. E. (2021). Wearable Technology and Analytics as a Complementary Toolkit to Optimize Workload and to Reduce Injury Burden [Review]. *Frontiers in Sports and Active Living*, *2*. https://doi.org/10.3389/fspor.2020.630576

Simegnaw, A. A., Malengier, B., Rotich, G., Tadesse, M. G., & Van Langenhove, L. (2021). Review on the Integration of Microelectronics for E-Textile. *Materials (Basel)*, *14*(17). https://doi.org/10.3390/ma14175113

Simegnaw, A. A., Malengier, B., Tadesse, M. G., & Van Langenhove, L. (2022). Development of Stainless Steel Yarn with Embedded Surface Mounted Light Emitting Diodes. *Materials (Basel)*, *15*(8). https://doi.org/10.3390/ma15082892

Singh Bal, B., & Dureja, G. (2012). Hawk Eye: A Logical Innovative Technology Use in Sports for Effective Decision Making. *Sport Science Review*, *21*.

Singha, K., Kumar, J., & Pandit, P. (2019). Recent Advancements in Wearable & Smart Textiles: An Overview. *Materials Today: Proceedings*, *16*, 1518-1523. https://doi.org/https://doi.org/10.1016/j.matpr.2019.05.334

Skinner, J., Edwards, A., & Smith, A. C. (2020). *Qualitative research in sport management*. Routledge.

Smith, B., & Sparkes, A. (2016). Interviews: Qualitative interviewing in the sport and exercise sciences. *Routledge handbook of qualitative research in sport and exercise*, 103-123.

Spaniol, F., Paluseo, J., Bonnette, R., Melrose, D., Ocker, L., & Szymanski, D. (2010). The Relationship Between Static Strength, Rotational Strength, Rotational Power, Bat Speed, And Batted-Ball Velocity Of NCAA Division I Baseball Players. *The Journal of Strength & Conditioning Research*, *24*. https://journals.lww.com/nsca-jscr/Fulltext/2010/01001/The_Relationship_Between_Static_Strength,.152.aspx

Sparling, P. B., Snow, T. K., & Millard-Stafford, M. L. (1993). Monitoring core temperature during exercise: ingestible sensor vs. rectal thermistor. *Aviation, space, and environmental medicine*, *64*(8), 760-763. http://europepmc.org/abstract/MED/8368992

Spil, T., Kijl, B., & Romijnders, V. (2019). The Adoption and Diffusion of Wearables. In (pp. 31-47). https://doi.org/10.1007/978-3-030-20671-0_4

Stoppa, M., & Chiolerio, A. (2014). Wearable electronics and smart textiles: a critical review. *Sensors (Basel)*, *14*(7), 11957-11992. https://doi.org/10.3390/s140711957

Sun, X., Lam, W. K., Zhang, X., Wang, J., & Fu, W. (2020). Systematic Review of the Role of Footwear Constructions in Running Biomechanics: Implications for Running-Related Injury and Performance. *J Sports Sci Med*, *19*(1), 20-37.

Svilar, L., Castellano, J., & Jukic, I. (2019). Comparison of 5vs5 Training Games and Match-Play Using Microsensor Technology in Elite Basketball. *The Journal of Strength & Conditioning Research*, *33*(7). https://journals.lww.com/nsca-jscr/Fulltext/2019/07000/Comparison_of_5vs5_Training_Games_and_Match_Play.19.aspx

Taborri, J., Keogh, J., Kos, A., Santuz, A., Umek, A., Urbanczyk, C., van der Kruk, E., & Rossi, S. (2020). Sport Biomechanics Applications Using Inertial, Force, and EMG Sensors: A Literature Overview. *Applied Bionics and Biomechanics*, *2020*, 2041549-2041549. https://doi.org/10.1155/2020/2041549

Tacca, J. R., Beck, O. N., Taboga, P., & Grabowski, A. M. (2022). Running-specific prosthesis model, stiffness and height affect biomechanics and asymmetry of athletes with unilateral leg amputations across speeds. *R Soc Open Sci*, *9*(6), 211691. https://doi.org/10.1098/rsos.211691

Tajadura-Jiménez, A., Väljamäe, A., & Kuusk, K. (2020). Altering One's Body-Perception Through E-Textiles and Haptic Metaphors [Original Research]. *Frontiers in Robotics and AI*, *7*. https://doi.org/10.3389/frobt.2020.00007

Tak, I., Wiertz, W.-P., Barendrecht, M., & Langhout, R. (2020). Validity of a New 3-D Motion Analysis Tool for the Assessment of Knee, Hip and Spine Joint Angles during the Single Leg Squat. *Sensors (Basel, Switzerland)*, *20*(16), 4539. https://doi.org/10.3390/s20164539

Tanner, E. A., Montes, J., Manning, J. W., Taylor, J. E., DeBeliso, M., Young, J. C., & Navalta, J. W. (2015). Validation of Hexoskin biometric shirt to COSMED K4 b2 metabolic unit in adults during trail running. *Sports Technology*, *8*(3-4), 118-123. https://doi.org/10.1080/19346182.2016.1248973

Terbizan, D. J., Dolezal, B. A., & Albano, C. (2002). Validity of Seven Commercially Available Heart Rate Monitors. *Measurement in Physical Education and Exercise Science*, *6*(4), 243-247. https://doi.org/10.1207/S15327841MPEE0604_3

Theodoropoulos, J. S., Bettle, J., & Kosy, J. D. (2020). The use of GPS and inertial devices for player monitoring in team sports: A review of current and future applications. *Orthopedic reviews*, *12*(1), 7863-7863. https://doi.org/10.4081/or.2020.7863

Tjønndal, A. (2022). The impact of COVID-19 lockdowns on Norwegian athletes' training habits and their use of digital technology for training and competition purposes. *Sport in Society*, *25*(7), 1373-1387. https://doi.org/10.1080/17430437.2021.2016701

Toon, N., McMaster, S., Outram, T., & Faghy, M. (2022). Assessing the Validity of a Kinematic Knee Sleeve in a Resistance-Trained Population. *Engineering Proceedings*, *15*(1).

Totaro, M., Poliero, T., Mondini, A., Lucarotti, C., Cairoli, G., Ortiz, J., & Beccai, L. (2017). Soft Smart Garments for Lower Limb Joint Position Analysis. *Sensors (Basel)*, *17*(10). https://doi.org/10.3390/s17102314

van der Kruk, E., & Reijne, M. M. (2018). Accuracy of human motion capture systems for sport applications; state-of-the-art review. *European Journal of Sport Science*, *18*(6), 806-819. https://doi.org/10.1080/17461391.2018.1463397

Van Hooren, B., Goudsmit, J., Restrepo, J., & Vos, S. (2020). Real-time feedback by wearables in running: Current approaches, challenges and suggestions for improvements. *Journal of sports sciences*, *38*(2), 214-230. https://doi.org/10.1080/02640414.2019.1690960

Vellios, E. E., Pinnamaneni, S., Camp, C. L., & Dines, J. S. (2020). Technology Used in the Prevention and Treatment of Shoulder and Elbow Injuries in the Overhead Athlete. *Curr Rev Musculoskelet Med*, *13*(4), 472-478. https://doi.org/10.1007/s12178-020-09645-9

Vowles, C. J., Van Engelen, S. N., Noyek, S. E., Fayed, N., & Davies, T. C. (2022). The Use of Conductive Lycra Fabric in the Prototype Design of a Wearable Device to Monitor Physiological Signals. *Annu Int Conf IEEE Eng Med Biol Soc*, *2022*, 922-925. https://doi.org/10.1109/embc48229.2022.9871042

Vu, C. C., & Kim, J. (2020). Highly Sensitive E-Textile Strain Sensors Enhanced by Geometrical Treatment for Human Monitoring. *Sensors (Basel)*, *20*(8). https://doi.org/10.3390/s20082383

Wang, J., Soltanian, S., Servati, P., Ko, F., & Weng, M. (2020). A knitted wearable flexible sensor for monitoring breathing condition. *Journal of Engineered Fibers and Fabrics*, *15*, 1558925020930354. https://doi.org/10.1177/1558925020930354

Weldon, A., Duncan, M. J., Turner, A., Lockie, R. G., & Loturco, I. (2022). Practices of strength and conditioning coaches in professional sports: a systematic review. *Biology of sport*, *39*(3), 715-726. https://doi.org/10.5114/biolsport.2022.107480

Whitelaw, S., Pellegrini, D. M., Mamas, M. A., Cowie, M., & Van Spall, H. G. C. (2021). Barriers and facilitators of the uptake of digital health technology in cardiovascular care: a systematic scoping review. *European Heart Journal - Digital Health*, *2*(1), 62-74. https://doi.org/10.1093/ehjdh/ztab005

Williams, D. S. B., Murray, N. G., & Powell, D. W. (2016). Athletes who train on unstable compared to stable surfaces exhibit unique postural control strategies in response to balance perturbations. *Journal of Sport and Health Science*, *5*(1), 70-76. https://doi.org/https://doi.org/10.1016/j.jshs.2016.01.010

Wilson, B. D. (2008). Development in video technology for coaching [https://doi.org/10.1002/jst.9]. *Sports Technology*, *1*(1), 34-40. https://doi.org/https://doi.org/10.1002/jst.9

Wilson, N., Thomson, A., & Riches, P. (2017). Development and presentation of the first design process model for sports equipment design. *Research in Engineering Design*, *28*(4), 495-509. https://doi.org/10.1007/s00163-017-0257-4

Windt, J., MacDonald, K., Taylor, D., Zumbo, B. D., Sporer, B. C., & Martin, D. T. (2020). "To Tech or Not to Tech?" A Critical Decision-Making Framework for Implementing Technology in Sport. *Journal of athletic training*, *55*(9), 902-910. https://doi.org/10.4085/1062-6050-0540.19

Woessner, M. N., Tacey, A., Levinger-Limor, A., Parker, A. G., Levinger, P., & Levinger, I. (2021). The Evolution of Technology and Physical Inactivity: The Good, the Bad, and the Way Forward. *Front Public Health*, *9*, 655491. https://doi.org/10.3389/fpubh.2021.655491

Woods, C. T., McKeown, I., Rothwell, M., Araújo, D., Robertson, S., & Davids, K. (2020). Sport Practitioners as Sport Ecology Designers: How Ecological Dynamics Has Progressively Changed Perceptions of Skill "Acquisition" in the Sporting Habitat [Hypothesis and Theory]. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.00654

Yunwei, L. I., & Shiwei, J. (2019). Video Analysis Technology and Its Application in Badminton Sports Training. *Journal of Physics: Conference Series*, *1213*(2), 022009. https://doi.org/10.1088/1742-6596/1213/2/022009

Zhang, D., & Tian, Y. (2022). Application of Image Processing Technology in Aerobics Injury Diagnosis. *Emerg Med Int*, *2022*, 2553048. https://doi.org/10.1155/2022/2553048

Zhang, Y., Wang, H., Lu, H., Li, S., & Zhang, Y. (2021). Electronic fibers and textiles: Recent progress and perspective. *iScience*, *24*(7), 102716. https://doi.org/https://doi.org/10.1016/j.isci.2021.102716

Zhang, Z., & Poslad, S. (2013). Design and test of a hybrid foot force sensing and GPS system for richer user mobility activity recognition. *Sensors (Basel)*, *13*(11), 14918-14953. https://doi.org/10.3390/s131114918

Zhou, L., Fischer, E., Tunca, C., Brahms, C. M., Ersoy, C., Granacher, U., & Arnrich, B. (2020). How We Found Our IMU: Guidelines to IMU Selection and a Comparison of Seven IMUs for Pervasive Healthcare Applications. *Sensors (Basel, Switzerland)*, *20*(15), 4090. https://doi.org/10.3390/s20154090