The use of a Digital Knee device during rehabilitation post Anterior Cruciate ligament reconstruction

Anja van Gulden
PGDipSpEx, BSc

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Attestation of Authorship

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any other degree or diploma of a university or other institution of higher learning, except where due acknowledgement is made.

Anja van Gulden

May 2022

Candidate Contributions to Co-Authored Papers

Chapter 3.	van Gulden, A., Wyatt, H., Whatman, C., McDaid, A. The reliability of sagittal plane knee motion using a Digital Knee device. To be submitted to Journal of neuroengineering and rehabilitation.	van Gulden 80% Wyatt 8% Whatman 8% McDaid 4%
Chapter 4.	van Gulden, A., Wyatt, H., Whatman, C., McDaid, A. The use of a Digital Knee device in early stage rehabilitation post anterior cruciate ligament reconstruction. To be submitted to the Journal of Physical Therapy and Sport.	van Gulden 80% Wyatt 8% Whatman 8% McDaid 4%

We, the undersigned, hereby agree to the percentages of participation to the chapters identified above:

Anja van Gulden	Hannah Wyatt	Chris Whatman
Andrew McDaid		

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Confidential Material

An embargo is required on the public availability of the print and digital copies of this thesis from when the thesis is lodged in the Library for a period of 36 months.

Abstract

The anterior cruciate ligament (ACL) is a fundamental knee stabiliser and injury to the ACL often requires surgical repair. Sagittal plane knee range of motion (ROM) measurements enable clinicians to assess knee control and supporting muscular activation. Advances in digital technology have demonstrated the potential to improve rehabilitation outcomes via individualised specific feedback and increased ROM monitoring. Digital devices have been developed which may be beneficial for ACL rehabilitation, such as the Digital Knee device (OPUM, 2021). However no literature has been found investigating the use of a smart wearables in ACL rehabilitation. However, many benefits such as improved motivation, adherence and convenience have been found in other wearable rehabilitation devices, suggesting potential for translation to ACL rehabilitation. The overall purpose of this thesis was to assess the usability of a Digital Knee device during ACL rehabilitation.

To investigate the measurement reliability of sagittal plane knee motion recorded on the Digital Knee device, a heel slide and sit to stand activity were completed by each participant. Following these two activities participants rested for 15-minutes with the device removed. A second session of the same two activities was completed after re-attaching the Digital Knee device. High reliability for measurement of sagittal plane knee motion was found for both the within-session (ICC = 0.96 -1.00) and between-session (ICC = 0.70 -1.00) conditions. Two instruction protocols were also trialled among the participants (text dominant and infographic dominant) to determine the effect on the device reliability. No significant differences in reliability were found between the text dominant and infographic instruction protocols. The observations in this study aligned with previous findings, denoting measurements taken on the Digital Knee will be highly repeatable during recurrent testing.

To better understand the effectiveness of the Digital Knee device during rehabilitation, eight participants were recruited to use the device for six weeks post-surgery and were asked to perform a daily heel slide activity. Daily maximum sagittal knee motion was recorded on the Digital Knee device and saved to an online server. A goniometer was used to record weekly maximum sagittal knee motion in a control group. Similar average weekly knee motion was reported based on goniometer and Digital Knee

measurements however the recorded range was lower than expected and larger inter-subject variation was observed in the Digital Knee group. Within the six-week timeframe of the study, maximum group knee flexion was reported at 87° ± 14 (goniometer) and 86°±11 (Digital Knee). Participants also completed weekly questionnaires and a post-study semi structured interview to provide insight into the use of the device during their rehabilitation. Device users reported high levels of motivation throughout the study which they attributed to the ability to view live feedback. Compliance with the Digital Knee during the six-week period was also good (79%), which was speculated to be because of live monitoring and improved motivation. Digital Knee device users identified comfort of the device and usability of the digital interface as recommended features for future improvements. The findings from this study have been utilised by the Digital Knee device manufacturer to improve its usability in rehabilitation. Specifically, a compression sleeve has been developed to replace the rigid strap design and interface changes have been made to allow viewing of long-term personal data. Overall, this research has contributed to the development of design improvements which should improve wearability and measurement accuracy of the Digital Knee device.

Chapter 1: Introduction and Rationale

In 2019 there were over 2300 anterior cruciate ligament (ACL) injuries requiring reconstruction in New Zealand, with around 95% relating to sport and exercise activities (ACC, 2020). The New Zealand environment and culture facilitates a large proportion of the population to be active (Brocklesby, 2019). Brocklesby's (2019) research found approximately 72% of adults over the age of 18 participated in at least 30 minutes of a sporting activity each week. Fifty nine percent of those assessed spent a minimum of 2.5 hours engaging in physical activities each week, with adults between the ages of 18 and 34 years reported as the most active. Findings from Brocklesby (2019) relate to the New Zealand ACL injury statistics, as over 50% of annual ACL injuries are reported within the 18-34 years of age group (ACC, 2020). The most common ACL injury mechanisms reported were loss of balance/postural control and a twisting knee movement, accounting for 36% and 32% of injuries, respectively (ACC, 2020). These are movements which commonly occur in sporting situations. Furthermore, statistics show between 90-95% of ACL injury claims for individuals between 18-34 years old are reported to result from sport-like activities (ACC, 2020). A complete ACL tear, also known as an ACL rupture, has limited ability to heal without surgical intervention (Hsu, Liang, & Woo, 2010). In New Zealand the Accident Compensation Corporation (ACC) cover the cost of ACL reconstruction surgery. Each year around $29,000,000 is spent on ACL injuries in New Zealand, averaging approximately $25,000 per ACL claimant (ACC, 2021). Due to the nature of ACL reconstruction, return to sport-like activities is reliant on factors such as muscular strength, neuromuscular connection, patient engagement with rehabilitation and graft heeling. To provide individuals with the greatest chance of getting back into physical activity post ACL injury, effective rehabilitation is imperative to ensure these factors are considered and progressed at the correct stages (Fauset, Wilkins, Reid, Larmer, & Potts, 2019).

Early-stage ACL rehabilitation (0-6 weeks post-surgery) has been identified as a crucial stage of the rehabilitation process, and can be a strong predictor of long term patient outcomes (Eckenrode, Carey, Sennett, & Zgonis, 2017). It is standard practice for a physiotherapist to monitor and control patient progress. There are a few early benchmarks that need to be achieved before the patient can progress to more advanced movement such as adequate passive knee extension and good quadriceps activation. Inability to achieve the established benchmarks has been shown to have long term effects on gait and return to pre-injury activity levels (Adams et al., 2012; Cavanaugh & Powers, 2017; Eckenrode et al., 2017; Riskowski, 2010). Knee range of motion (ROM) is one of the key benchmarks used by a physiotherapist to gauge patient progress. Typical rehabilitation guidelines suggest patients should be able to achieve full knee extension and good knee flexion (~130°) within the first six weeks (Eckenrode et al., 2017). Once this is achieved the rehabilitation focus is shifted towards building adequate muscle strength and regaining good knee control to allow return to impact movements such as running (approximately week 12) (Cavanaugh & Powers, 2017). Currently ROM measurements, which are particularly important during the early stages of rehabilitation, can only be measured during in-person physiotherapy appointments using a goniometer. Although this is standard practice and has been found accurate when performed correctly, it restricts the opportunity for more regular progress measurements to be taken in between physiotherapy visits (Kumar et al., 2015). A modernised method of recording ROM is through smart wearable devices. Use of smart wearable devices and integration of technology in medical practice has increased considerably in the last decade, creating an opportunity for new technologies to be developed and applied to different health settings (Msayib, Gaydecki, Callaghan, Dale, & Ismail, 2017).

Digital healthcare companies are also on the rise with an increasing number of companies specialising in rehabilitation devices. One such company, based in New Zealand founded by Associate Prof Andrew McDaid is OPUM. The company was founded out of the medical devices and technologies research group based at the University of Auckland. The Digital Knee (OPUM, 2021) was designed based on 10 years of culminative research and is a smart wearable device which is attached to the leg via a semi rigid knee brace (Figure *1*). The device was designed as a tool "for tracking knee injury rehabilitation" (OPUM, 2021). The Digital Knee device has a Bluetooth module which allows the user to securely connect their device to the Digital Knee phone application (OPUM active). The Digital Knee device enables ROM measurements to be recorded in any environment and provide direct feedback (through a live graphic) to the user via a smartphone without the need of a clinician being present at the time of measurement, as well as allowing approved clinicians to view their patients’ recordings. COVID 19 has had a significant impact on rehabilitation with the long lockdowns requiring remote patient monitoring via telehealth consultations as well as changes to a more remote operation of health services (Fahey et al., 2021). Integration of wearable tools such as the Digital Knee into rehabilitation has the potential to assist clinicians and patients during musculoskeletal rehabilitation.

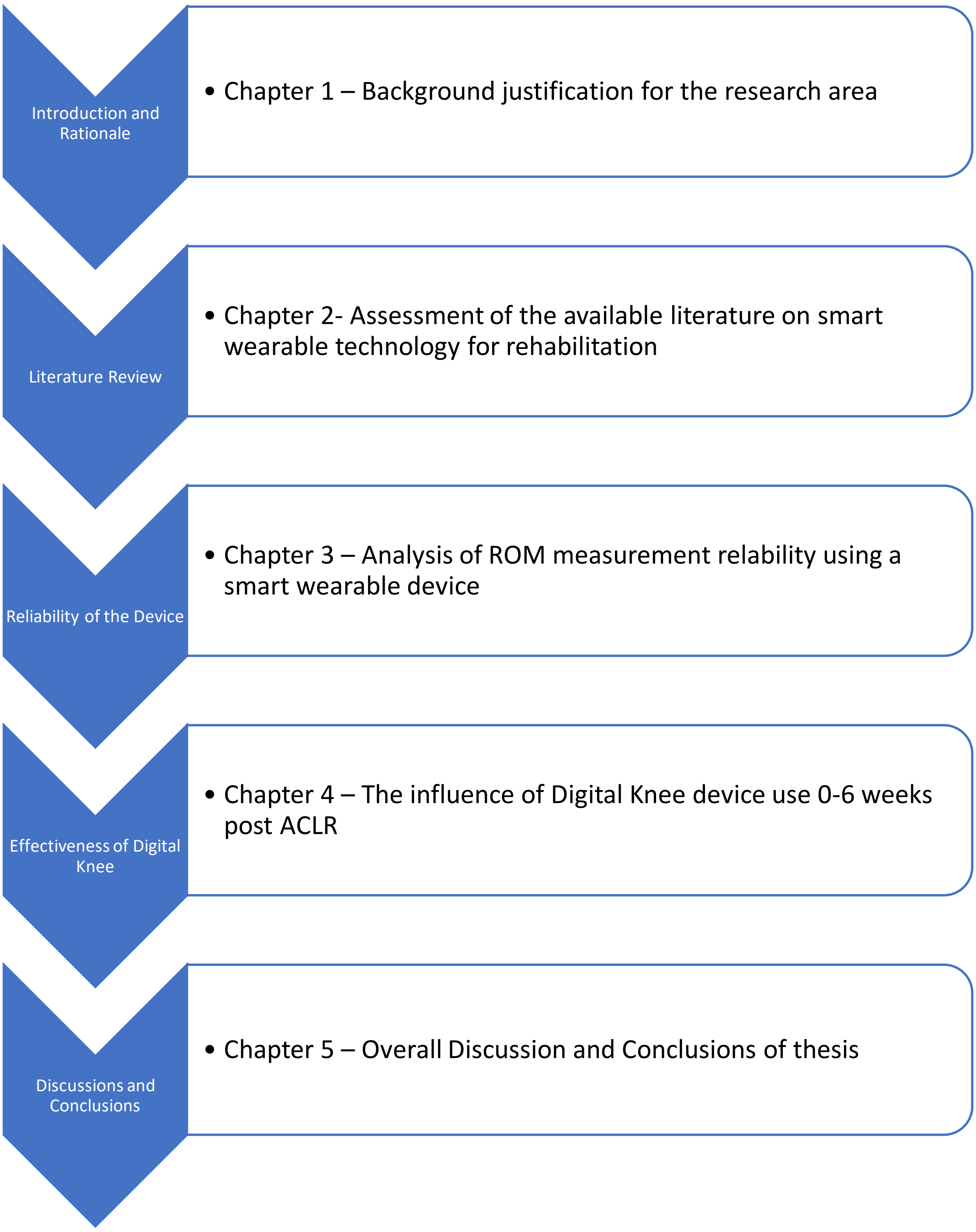
Figure 1: The Digital Knee device and OPUM active mobile application

As well as improving the ease in which rehabilitation progress can be monitored, previous research has found patients are commonly more motivated to perform at home exercises when they are able to view live feedback and see their progress from a digital device (De Benedictis et al., 2020). Additionally clinicians have found digital devices useful to provide feedback to their patients, and have reported increased adherence and engagement to the clinician-prescribed rehabilitation programme (Hanzlíková et al., 2016; Lizzio, Cross, Guo, & Makhni, 2020). Only a few studies have investigated smart devices similar to the Digital Knee device and there is limited research specific to the devices for the knee joint, specifically during the early post-operative rehabilitation stage after anterior cruciate ligament reconstruction (ACLR) surgery. The majority of the available research suggests smart wearable devices could have beneficial effects during rehabilitation, however assessment in comparison to standard practice is yet to occur (Msayib et al., 2017). This highlights the need for further investigation into smart wearable devices for assisting rehabilitation directly post ACLR, specifically for ROM assessment and movement quantification. Further investigation will also expand the knowledge and confidence in measurement outputs required by clinicians and users to endorse the device.

Research Questions Addressed in this Thesis

RQ1: To what extent does the Digital Knee device reliably measure knee range of motion?
RQ2: How does user instruction presentation affect the reliability of Digital Knee range of motion measurements?
RQ3: How does Digital Knee device use affect knee joint range of motion post recovery ACLR?
RQ4: How does Digital Knee device use affect rehabilitation motivation and adherence?

Structure of Thesis



In accordance with the Auckland University of Technology's Format Two, this thesis contains an introduction/rationale, a literature review and two chapters (Chapters 3 and 4) which have been formatted to be suitable for journal publication. The chapters are presented as they have been submitted to, or formatted for, the target journal, and as such, the repetition of some information occurs. Each chapter in the dissertation begins with a prelude, which helps form the sequential progression and cohesion of the thesis as a whole. Lastly, the thesis concludes with a general discussion integrating findings from the preceding chapters, while also outlining the practical implications of this research, study limitations and directions for future research. The referencing format has been standardised to the American Psychological Association 7th Edition, with a single reference list prepared for the dissertation.

Chapter 2: A Review of Smart Wearable Devices and Incorporation of Telehealth into Rehabilitation

Introduction

The popularity of smart wearable devices has blossomed in the last decade, with wearable devices such as smart watches, heart rate trackers and movement sensors commonly being worn on a daily basis (Turner et al., 2021). Living in a digital era has seen a greater acceptance of the integration of technology into everyday living and an increased fascination with personal data generation and analysis. This increased popularity creates an opportunity for digital technology to be used not only for activity tracking, but also for integration into rehabilitation devices and telehealth. Wearable devices are considered to have many positive influences on rehabilitation with reports of increased confidence motivation and adherence (Argent, Daly, & Caulfield, 2018; Dunphy & Gardner, 2020; Naeemabadi et al., 2020). This is thought to be attributed to features such as live feedback which is displayed through the device allowing the user to monitor their daily progress. Additionally, the data is also viewable to a clinician during situations where telehealth is being used (Haladjian, Bredies, & Bruegge, 2018).

Telehealth is the digitalisation of standard health practice including virtual consultations or follow up appointments after an initial face to face appointment. It allows individuals in remote environments to have the same access to health services as those in more urban settings and enables healthcare services to continue safely in situations like COVID-19. Online consultations have been found as a useful tool to bridge the patient to clinician gap, however wearable devices could further improve the effectiveness of rehabilitation by improving patient – clinician communication (Dunphy & Gardner, 2020).

Telehealth together with smart wearable devices presents an alternative option for patients and highlights the need for traditional practices to adapt to suit a more digital world. Therefore, the aim of this research review is to assess the currently available literature on smart wearable devices in musculoskeletal rehabilitation. The systematic review will investigate the types of smart wearable devices currently available for musculoskeletal injury rehabilitation, and the contributing factors to successful/impactful wearable rehabilitation devices. From this review the researchers will have an enhanced knowledge of the available devices and literature, and use this to make decisions regarding the accompanying research chapters.

Methods

An electronic search was conducted using the databases: Google Scholar, PubMed, Science Direct, SagePub and Scopus for journal articles from 2000 to 2021. Key words included rehabilitation, biofeedback, wearable sensors, adherence, orthopaedics, musculoskeletal, mobile health, telehealth, live feedback, motion capture, goniometer, injury and associated variations. Additionally, reference lists from reviewed articles were also used to find literature. Research articles were included if they focussed on patients using a non-rigid smart wearable device post orthopaedic surgery, participants using a non-rigid smart wearable device to assess reliability/validity of a smart wearable, or research focusing on ROM measuring devices.

Results and Discussion

Twenty-four published studies were identified for review that focused both on wearable devices and telehealth research independently or collectively, twelve studies were specific to smart wearable devices, and nine were specific to the knee joint (see appendix). All reviewed studies which involved device testing included cohorts of both males and females with ages ranging from 18 to 68 years. Studies were excluded from the literature search if they used a smart wearable attached to a locking brace for rehabilitation.

Technology has been used to quantify movement such as ROM via two prominent methods, 3D motion capture systems and goniometry (Poitras et al., 2019). 3D motion capture has been identified as the gold standard to quantify movement, however it is generally confined to a laboratory style environment due to the equipment involved (Poitras et al., 2019). Goniometer measurements are more commonly used to record ROM measurements in a rehabilitation practice and should only be used by skilled practitioners (Kumar et al., 2015). Smart wearables devices are suggested to be a convenient solution to the shortcomings identified with motion capture and goniometer measurements. Smart devices allow accurate measures of movement to be recorded via inertial motion sensors (IMU) (Porciuncula et al., 2018). IMU sensors typically consist of gyroscopes, accelerometers and magnetometers (Porciuncula et al., 2018). Gyroscopes measure the change in angular motion, accelerometers record the rate of change in speed, and magnetometers orientate the sensor by detecting its orientation relative to gravity (Porciuncula et al., 2018). The accuracy along with the portability of these devices are the key to their use within smart rehabilitation devices.

Reliability

Across studies, findings have shown the reliability of IMU-informed wearable devices for measuring knee ROM to range from moderate to high (ICC = 0.70-0.99, Table 1) (Jaysrichai, Suputtitada, & Khovidhungij, 2015; Kayaalp et al., 2019). Research assessing the reliability of knee ROM using a dual sensor wearable device was performed on thirteen participants at different stages post orthopaedic knee surgery. Participants wore two IMU sensors attached with adhesive bandage straps above and below the knee and completed 10 metre walking tests during which peak range of knee flexion and extension was recorded. A high level of within and between trial reliability was reported (r = 0.86) (Kayaalp et al., 2019). A second study with high reliability findings (ICC = 0.84-0.99) used a similar walking test as well as a step test to assess the ROM of 10 participants wearing a smart wearable device and compared findings to 3D motion capture (Jaysrichai et al., 2015). As shown in Table 1, only one other study reported reliability findings for smart wearables using IMU sensors (Kayaalp et al., 2019).

The lack of consistency in presentation of reliability findings across different literature publications makes a global conclusion more challenging to reach, and strongly supports the recommendation for more research investigating reliability. In contrast to the varied presentation of reliability findings across publications, a consistent finding across the research was the technology used within the devices. Additionally, majority of literature appraised on use of smart wearable devices for musculoskeletal rehabilitation has focussed on the knee joint. A possible reason for this could be due to the type and length of rehabilitation involved with knee injuries.

IMU sensors were the only sensors used in the reviewed research articles, and have reported high levels of accuracy with two studies reporting error ranges of up to 4° and 6° compared to video motion capture (Jaysrichai et al., 2015; Turner et al., 2021). The reliability of available devices was also reviewed, however only two of the seven identified studies assessed reliability. Furthermore the two studies which reported ICCs were completed using a healthy population. This limits the ability to assess if high reliability can be achieved across healthy and injured populations. A further interesting finding was the lack of research on devices with a single IMU sensor, as only two of the highlighted studies used a single shin sensor to measure the knee joint. However, a notable finding by one researcher was the accuracy of a single sensor compared to multiple sensors. The researchers found the accuracy of sagittal knee motion data recording remained consistent when one, two or three IMUs were used, therefore allowing the development of more cost-effective devices without compromising accuracy (Giggins et al., 2014).

Benefits of smart wearables

A common finding across six studies which assessed telehealth was increased confidence and motivation for users, largely due to better and consistent communication. A study by Dunphy and Gardner (2020) evaluated the use of telehealth following ACL injury using a survey approach. Participants reported improved confidence and motivation to complete their rehabilitation exercises during telehealth sessions (Dunphy & Gardner, 2020). Two studies have shown that adherence to home based rehabilitation was very low despite the success of any medical intervention being largely dependent on patient adherence (Argent, Daly, et al., 2018; Faisal et al., 2020). This is a common finding across this research area with one study identifying around 65% of patients were inconsistent with completing their home rehabilitation programmes and up to 10% do not complete them at all (Giggins, Sweeney, & Caulfield, 2014). In a group post ACL injury, telehealth was shown to improve confidence, motivation to complete rehabilitation exercises and patient adherence by instilling change in participant behaviour using personalised goals, exercise logs and reminder prompts (Dunphy & Gardner, 2020).

Further benefits post knee joint replacement have also been reported (Naeemabadi et al., 2020). Naeemabadi et al. (2020) reported using a smart wearable device during rehabilitation resulted in better and clearer communication between patient and clinician as well as reports of increased levels of adherence, self-confidence and motivation post-surgery similar to Dunphy and Gardner (2020). The respective impacts were attributed to the flexibility, usability and convenience of the telehealth rehabilitation system (Naeemabadi et al., 2020). A common consensus between the reviewed research was that increased adherence, motivation and commitment was largely influenced by the live feedback capability within the smart wearable devices. This further increases the popularity of developing smart wearable devices as adherence to rehabilitation exercises is crucial to a successful rehabilitation (Faisal et al., 2020).

Table 1: Summary of literature on wearable sensors assessing knee ROM

Study	Participant	Population	Sensor Type and Number	Reliability	Validity
Jaysrichai, T., et al.	10 participants (7 male, 3 female) Average age 26.8 years	Healthy	4 sensors attached below the knee and 4 attached above the knee. Each sensor consists of a triaxial accelerometer, triaxial gyroscope and triaxial magnetometer.	High ICC correlation (0.84-0.99).	Mobile sensor recorded range of motion within 6 degrees of error compared to motion capture.
Di Paolo, S., et al.	34 participants (18 male, 16 female) Average age 22.8 years	Healthy (no previous lower limb injury)	15 Inertial sensors (accelerometer and gyroscopes) placed around the body and compared to Vicon motion capture.	Not Assessed.	Excellent sagittal knee movement validity compared to VICON, r= 0.95 – 0.99. knee movement overall fair to excellent.
Turner, A. J., et al.	16 participants (6 male, 10 female Average Age: NA	Healthy	Soft robotic stretch sensor imbedded into compression knee brace.	Not Assessed.	High validation reporting <4 degrees variation when compared to measurements recorded via VICON. Higher accuracy during open chain kinetic movements.
Whelan, D. F., et al	83 participants (60 male, 23 Female) Average Age: 24.7 years	Healthy	IMU sensors placed on thigh and ankle. Each IMU consists of a triaxial accelerometer, triaxial gyroscope and triaxial magnetometer.	Not Assessed.	77 % accuracy with single IMU compared to multiple.
Chapman, R. M., et al.	10 Participants (3 Male 7 female Average age 67 years	Total Knee arthroplasty rehabilitation	Two IMU sensors place one above and one below the knee on rigid straps. IMU sensors provides more information when compared to clinic goniometry.	Not Assessed.	Not Assessed, pre validated IMU used.
Ianculescu, M., et al.	30 Participants Average age: NA	2 days Post ACLR	Re.flex system. Single IMU sensor (triaxial goniometer and triaxial accelerometer placed in line with joint centre). Validated via motion capture.	Not Assessed.	Not Assessed.
Kayaalp M.E., et al.	13 Participants (9 Male, 4 females) Average age 32.7 years	Healthy	Two IMU sensors, one above and one below the knee. IMU consists of a triaxial accelerometer, triaxial gyroscope and triaxial magnetometer.	Reliability of range of motion during repeated walking tests. Between trial r= 0.96. Within trial r= 0.85.	Not Assessed.
Haladjian, J., et al.	10 Participants (3 Male 7 Female Age range:20-26 years, one 51 year old	Different stages post ACL injury (specifics not identified)	2 IMU sensors incorporated in knee compression sleeve. Sensors located above and below knee joint.	Not assessed.	Average error for ROM compared to 2D photograph measurements 4.82°(± 3.92°).

Features of smart wearables

Although lab-based research has shown promising results for the benefits of smart wearables, evaluation of clinician trials of wearable devices are needed, to ensure successful application in practice. Research conducted by Argent et al (2018) on a group of clinicians trialling a smart wearable knee device reported the clinicians suggested the device to be useful for knee rehabilitation. Live feedback and remote ROM measurement were the two most popular features, with clinicians suggesting they would help to gain a better understanding of the patients progress (Argent, Slevin, et al., 2018). An assessment of a smart wearable device on gait retraining in healthy women demonstrated participants were able to make instantaneous adjustments to their gait and level of loading between the left and right leg whilst receiving live feedback, compared to a reactive approach (review of movement followed by altered instruction) by a clinician (Riskowski, 2010). Although this respective Riskowski (2010) study was limited to a healthy population, similar findings to the clinicians' suggestions have been reported in research by Argent, Slevin, et al. (2018). Patients who wore a compression sleeve containing a wearable device at various stages post ACLR have additionally reported the live feedback feature to be a huge benefit of a smart wearable device, particularly during the early stages (0-6 weeks) (Haladjian et al., 2018). Another key element which is thought to impact the success of smart wearable devices is the presentation and accessibility of the live data (Ayoade & Baillie, 2014; Haladjian et al., 2018).

Development of interactive mobile applications enables a digital illustration of the user's movement on screen alongside a simple, easy to understand data summary. A group of clinicians assessing a smart wearable device reported the ability to refer back to live patient data during the telehealth consultation allowed them to make better informed decisions about their patients' progress (Anthonius Lim & Pranata, 2020; Haladjian et al., 2018). Ease of application use and visualisation of live movement have been identified as contributing factors to improving connection and clear communication between patient and clinician, resulting in increased drive within patients to complete their rehabilitation exercises. Furthermore a number of studies have reported live feedback from smart wearables positively influences patient adherence and motivation, with some studies reporting improvements in adherence to rehabilitation programmes of 32% (Argent, Daly, et al., 2018; Faisal et al., 2020; Ianculescu, Andrei, & Alexandru, 2019; Yeh et al., 2012).

One of the most important factors which must be considered with the introduction of wearable technology is the impact on quality of care in comparison with commonly practiced face-to-face consultations. Two studies investigating orthopaedic rehabilitation patients have found no difference in the quality of care between telehealth/video consultations and face to face consultations (Fahey et al., 2021; Phuphanich, Sinha, Truong, & Pham, 2021; Tousignant et al., 2011). Researchers have reported telehealth services enabled clinicians to maintain communication with patients during their rehabilitation process which may not have been possible otherwise (Anthonius Lim & Pranata, 2020; Fahey et al., 2021; Phuphanich et al., 2021). Additionally the convenience and cost effectiveness of telehealth appointments have been reported as favourable factors (Kane et al., 2020).

A group of patients post rotator cuff repair reported telehealth consultations significantly reduced the time allocation needed for appointments as they no longer needed to obtain transport to and from the appointment or spend time in the clinic waiting room (Kane et al., 2020). Patients also reported appointment times were similar irrespective of the appointment type (video consultation or face to face consultation). A small percentage of patients reported feeling nervous prior to their initial video consultation, however the majority of patients preferred the video consultation method for follow up sessions after the initial video consultation (Kane et al., 2020). Due to the COVID-19 pandemic some researchers did raise concern at the rapid speed with which telehealth was adopted (Anthonius Lim & Pranata, 2020). There have been recommendations for more research to provide in-depth analysis on the quality of care post-surgery, predominantly through virtual consultation, and what effect tools such as wearables can have (Anthonius Lim & Pranata, 2020; Fahey et al., 2021; Phuphanich et al., 2021).

Concerns about data privacy have been reported in a number of studies assessing wearables and the increased use of telehealth practice (Dunphy & Gardner, 2020; Fahey et al., 2021; Kayaalp et al., 2019); however, the level of concern amongst participants was found to be low and only mildly impact patient satisfaction (Dunphy &

Gardner, 2020; Fahey et al., 2021; Kayaalp et al., 2019). As technology becomes more integrated into more aspects of life, data privacy concerns are projected to grow due to the increase in data that is being generated and shared, often unknowingly. Furthermore, health care/patient privacy is a high priority with and without the increased use of technology, therefore it has been recommended for increased emphasis to be placed on data security to reassure patients/users who opt to use digital products (Perez & Zeadally, 2017).

This review aimed to identify the availability of smart wearable devices for rehabilitation and the contributing factors to their success. From this review there is a consensus that both clinicians and patients are in support of smart wearable device use during rehabilitation. Although the availability of research into wearable devices for rehabilitations still limited, further research into new products will provide support for manufacturers by highlighting the key benefits for both clinicians and patients. Additionally, the integration of smart wearable devices alongside current clinical practices was reported to strengthen rehabilitation practices through, increased adherence, motivation, communication, affordability, and convenience. Finally this review highlighted the need for more research to be undertaken in clinical practice to assess the reliability, validity, and effectiveness of available technology within the rehabilitation population and add measurement confidence to telehealth practices.

Prelude to Chapter 3

The findings form the literature review identified no deficits reported in quality of care between remote or face to face health care, supporting the use of rehabilitation tools to facilitate remote care. The review also highlighted the lack of consistent reliability findings within the smart wearable device literature. High reliability is a key component of any measurement tool, to ensure confidence in results, therefore a study was conducted on a group of participants to assess the reliability of a Digital Knee device. This study also investigated the influence of instruction presentation, and the effect this could have on the reliability of a device.

Chapter 3: The reliability of sagittal plane knee motion assessment using a Digital Knee device

Introduction

Smart wearable devices have increased in popularity in the last decade with devices such as smart watches now a commonly used device for health and movement tracking (Patel, Asch, & Volpp, 2015). The Digital Knee (OPUM, 2021) is a smart wearable device which allows quantification of knee range of motion (ROM) to occur remotely and is therefore designed to assist practitioners in delivering their rehabilitation programmes (Kumar et al., 2015; Marques et al., 2020). Previous research has found remote sensors to be highly accurate when compared to goniometer measures and or a motion capture system (Fong & Chan, 2010; Jaysrichai et al., 2015; Kumar et al., 2015; Lee et al., 2014; Lizzio et al., 2020; Msayib et al., 2017; Patel, Park, Bonato, Chan, & Rodgers, 2012; Poitras et al., 2019; Watanabe & Saito, 2011). However, only a small number of studies have assessed the accuracy of sensor devices on the knee, finding them to be within a similar error range to a goniometer (approximately 6 to 10°) (Jaysrichai et al., 2015; Kumar et al., 2015).

Smart wearable devices such as the Digital Knee device, consist of an intelligent movement/positional sensor attached to non-restrictive knee brace. The Digital Knee device combines features of goniometer and motion capture measurement systems to remotely quantify movement and in particular, measure ranges of motion (Bittel, Bittel, Williams, & Elazzazi, 2017; Peeler & Anderson, 2008). Along with many other devices available on the market, the Digital Knee device consists of three main parts: 1) the data collection and sensor hardware; 2) communication software and hardware to relay information; and 3) data analysis software to extract relevant data from the device (Fong & Chan, 2010; S. Patel et al., 2012). The device contains a magnetic field sensor and an IMU sensor which collects information using imbedded moment arms. The moment arms are assumed to align with the thigh and shank of the leg when attached correctly, highlighting the importance of correct alignment for accurate measurements. The moment arm positional data is then transmitted via Bluetooth to a mobile device in real time and synced to a secure online data platform (Lizzio et al., 2020; Weinberg et al., 2007). Only two previous studies have assessed the reliability of IMU sensors for the knee joint however both of these studies used multiple sensors surrounding the knee (Di Paolo et al., 2021; Kayaalp et al., 2019). The Digital Knee differs from these devices as it only uses a single IMU sensor placed at the joint centre, relying on more precise alignment than a multi-unit device. Currently no published research has been conducted on the reliability of the Digital Knee device.

High reliability is a fundamental element to the success and implementation of a smart wearable device in both remote and non-remote rehabilitation settings (Marques et al., 2020). Incorrect IMU device placement has been reported to result in measurement errors of up to 10°, highlighting the importance of accurate positioning particularly for remote measurement tools which are often attached by untrained individuals (Marques et al., 2020). Previous research into instruction delivery has found instructions utilising both graphic and text aspects to facilitate faster learning and better understanding compared to instructions using text alone (Beiger, 1982; Wang et al., 2019). The incorporation of infographic dominant instruction into the largely text based Digital Knee device instruction booklet may therefore lead to increased reliability through more consistent and independent fitment.

Therefore, the aim of this current study was to assess the within and between-session reliability of knee joint sagittal plane range of motion measures from the Digital Knee device, and to investigate if the reliability of the Digital Knee device can be influenced through the addition of interactive graphic instruction. Irrespective of instruction protocol we hypothesize the within test reliability to be very high due to the Digital Knee not being moved between tests. We additionally hypothesize the infographic instruction protocol would improve participant understanding of brace placement.

Methods

Participants

Ten participants (6 male, 4 female) between the ages of 21 and 31 (mean 25.5 ± 3.6 years) were recruited to the study via flyers displayed at the university campus. Participants completed a consent form and health history questionnaire prior to participation. The health history questionnaire confirmed participant eligibility by ensuring they were injury free and had no underlying health conditions that would impact their knee range of motion. 14. Ethics approval was granted on the 6th of May 2021 under the reference 21/140.

Instruction Protocol

Each participant was required to attend one testing session, during which they completed knee sagittal plane range of motion testing with instructions provided by one of two protocols. Participants were randomly assigned via a random number generator to two groups, text dominant or interactive graphic instruction protocol. To mimic use of the device in telehealth, all participants were required to attach the device and complete the activities independently without intervention by the researcher.

Text dominant instruction protocol

Participants were presented with a text dominant instruction sheet explaining how to attach the device, how to operate the device and application, how to perform each of the tests, and the order in which the tests should be completed (Appendix B). Participants were provided with an account and log in details to the Digital Knee mobile application (OPUM active) to complete the tasks.

Interactive graphic instruction protocol

Participants were provided the same text-based instructions and tasks as participants in the text dominant protocol group but with a few changes to how the instructions were presented (Appendix B). Participants were provided with fewer descriptive instructions and instead directed to the OPUM active application. In the OPUM active application, participants were shown an educational knee anatomy graphic, step by step instructions on how to attach the brace/device (with graphics), and instructions on how to perform the two tasks with a supporting graphic (Fig 1). These interactive graphic tools were compulsory before viewing or starting the testing tasks.

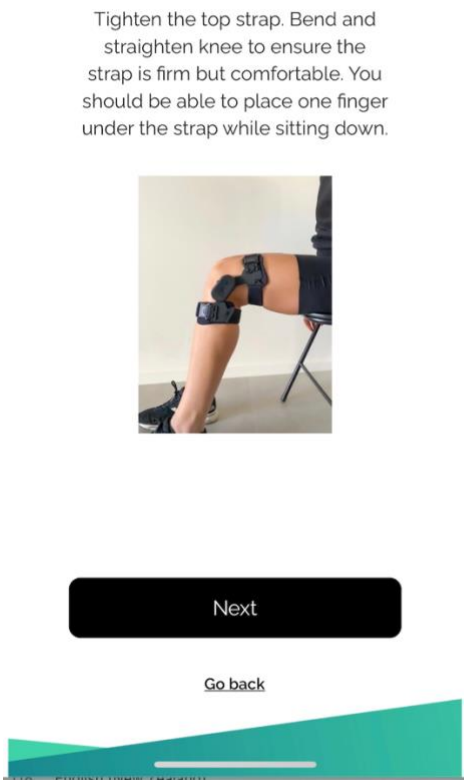


Figure 2: Screenshot of an example interactive graphic protocol via OPUM active

Range of motion testing

Knee joint range of motion was assessed during two tasks, a heel slide and a sit to stand. Both of these activities are standard activities found in the Digital Knee mobile application and are used in clinical settings for knee injury rehabilitation, as well as being simple to perform activities among a non-injured population (Biggs, Jenkins, Urch, & Shelbourne, 2009; Janssen, Bussmann, & Stam, 2002). To test both within-session and between-session reliability, participants performed two sets of four repetitions of each task. They then removed the Digital Knee device and rested for 15 minutes before the device was re-attached and the tasks repeated. The order of tasks and testing is illustrated in Figure 3

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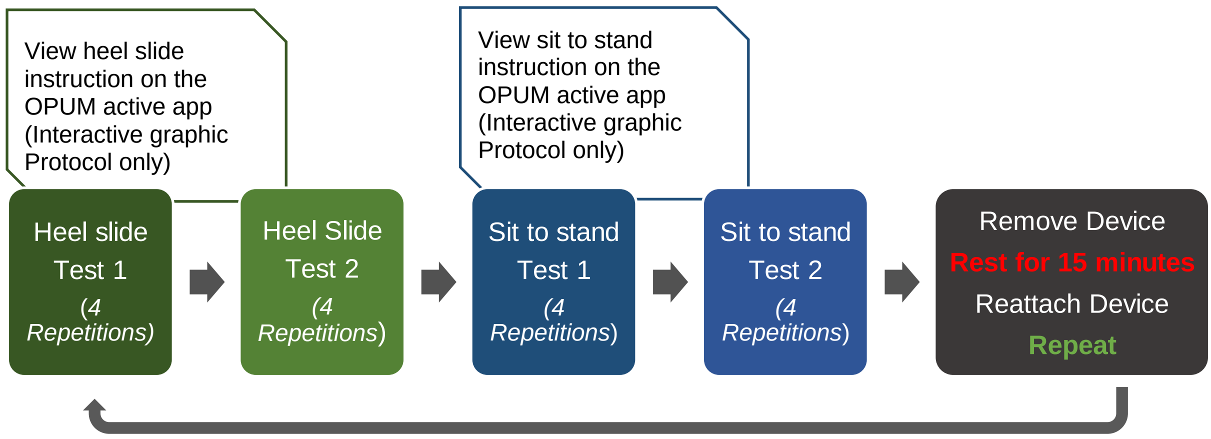

Figure 3: Order of tasks and tests for both instruction protocols in one session. The text dominant group read all task descriptions on a printed instruction sheet prior to commencing heel slide test 1.

Heel Slide Task

Participants lay on their back with their leg (with the device attached) directly next to a wooden plank (Figure 4). The participant slid their heel along the plank towards and away from their buttock trying to reach maximum range of knee flexion and extension respectively with each repetition.

Sit to Stand Task

Participants placed their heels firmly against a perpendicular wooden plank directly in front the chair (Figure 5). To complete the activity, they stood up and sat down onto the chair with their arms stretched out in front of their chest 4 times per test. Maximum flexion was recorded when the participant was seated in the chair and maximum extension was recorded when the participant was standing with their legs straight.

Figure 4: Testing set up and demonstration for the heel slide activity

Figure 5: Testing set up and demonstration for the sit to stand activity

Data Collection

Unilateral knee sagittal plane angle data was collected via the Digital Knee device and recorded via the OPUM active web interface.

Data Analysis

Peak knee flexion and knee extension angles were manually extracted from the continuous time-angle profiles and recorded in an excel spreadsheet. Mean, standard deviation, and change in mean across time were calculated for all tests. The means of the four repetitions from each test informed the reliability analysis. Data were entered into an Excel spreadsheet designed for consecutive pairwise analysis to determine the reliability of repeated measures (Hopkins, 2000). Typical error (TE) and interclass correlation coefficient (ICC) were calculated to assess the reliability of both within and between-session knee maximal flexion and extension. The associated 95% conference intervals were also calculated. The magnitude of ICC values were described as ≥0.99 = extremely high, 0.90-0.99 = very high, 0.75-0.90 = high, 0.50-0.75 = moderate, 0.20- 0.50 = low, ≤0.20 = very low (Hopkins, 2000). One participant was excluded for one trial during the heel slide activity as their foot did not remain in contact with the ground during the assessment (tests 1 and 2).

Results

The mean range of knee motion for heel slide and sit to stand tasks is presented in Table 2. The mean knee flexion was larger under the interactive graphic instruction protocol than text dominant protocol for both the heel slide and sit to stand activity. The conference limits (CL) were much larger for participants in the text dominant protocol (-9.9° to 21.9°) compared to the interactive graphic protocol (-3.1° to 6.3°).

Table 2: Overall mean knee motion and change in mean knee motion between sessions

Task	Knee Motion	Instruction Protocol	Mean (±SD)	Between Session Difference in Mean (95% CL)
Heel Slide	Flexion (°)	Text dominant	77.5 (28.9)	7.2 (-5.0-19.4)
		Interactive graphic	101.0 (13.7)	-2.1 (-5.4-1.2)
	Extension (°)	Text dominant	-1.4 (23.4)	6.0 (-9.9-21.9)
		Interactive graphic	8.8 (6.8)	-2.3 (-8.7-4.1)
Sit to Stand	Flexion (°)	Text dominant	55.7 (25.8)	2.3 (-5.3-9.9)
		Interactive graphic	80.9 (12.4)	-3.1 (-10.0-3.8)
	Extension (°)	Text dominant	-3.4 (21.3)	3.8 (-5.3-12.9)
		Interactive graphic	13.2 (8.5)	-2.8 (-11.9-6.3)

Within-session reliability

The within-session reliability ranged between very high to extremely high (ICC = 0.96 to 1.00) for both tasks (**Error! Reference source not found.**). TE range was similar across tests ranging from 0.4° to 2.8° (**Error! Reference source not found.**). The largest TE and the widest CL for knee flexion were recorded by participants under the text dominant protocol for both activities.

Table 3: Within-session reliability for knee flexion and extension during the heel slide and sit to stand activities.

Task	Knee Motion	Instruction protocol	TE (95% CL)	ICC (95% CL)	Reliability
Heel Slide	Flexion (°)	Text dominant	2.8 (1.7-8.0)	1.00 (1.00-1.00)	Extremely High
		Interactive graphic	1.2 (0.7-3.3)	1.00 (1.00-1.00)	Extremely High
	Extension (°)	Text dominant	1.2 (0.7-3.4)	1.00 (1.00-1.00)	Extremely High
		Interactive graphic	1.6 (1-4.7)	0.96 (0.65-1.00)	Very High
Sit to Stand	Flexion (°)	Text dominant	2.3 (1.3-8.7)	1.00 (1.00-1.00)	Extremely High
		Interactive graphic	1.5 (0.9-4.5)	1.00 (1.00-1.00)	Extremely High
	Extension (°)	Text dominant	0.4 (0.2-1.3)	1.00 (1.00-1.00)	Extremely High
		Interactive graphic	0.9 (0.6-2.7)	1.00 (0.99-1.00)	Extremely High

TE = Typical Error, ICC = Intraclass Correlation Coefficient, CL=Conference Limit, ICC magnitudes: ≥0.99 = extremely high, 0.90-0.99 = very high.

Between-session reliability

Between session reliability was also generally very high to extremely high (Table 3). Two exceptions to this were during knee extension under the interactive graphic instruction protocol for both activities. Moderate reliability (ICC=0.70) was calculated for the heel slide activity, and high reliability (ICC=0.81) was calculated for the sit to stand activity. Across all tests TE ranged between 2.5° and 9.1°.

TE for the heel slide activity was higher for both sagittal knee movements for participants in the text dominant group than the interactive graphic group. Heel slide TE values for the text dominant group were 9.1°(flexion) and 9.1°(extension) compared to 2.5°(flexion) and 4.8°(extension) in the interactive graphic protocol group. CL's were also found to be much wider for the text dominant group compared to interactive graphic protocol group in the heel slide activity. Despite the between protocol differences in the heel slide activity TE, the reliability of knee flexion was found to be extremely high for all between session activities and protocols. In contrast, the TE during knee extension was found to be similar between both protocols during the heel slide activity, however the reliability was found to be lower than knee flexion (very high and moderate, respectively). The TE during extension differed by only 0.4° for both protocols during the sit to stand activity. However, the text dominant group were found to have extremely high reliability (ICC = 0.99) compared to high reliability for the interactive graphic protocol group (ICC = 0.81).

Table 4: Between-session reliability for knee flexion and extension during the heel slide and sit to stand activities.

Task	Knee Motion	Instruction protocol	TE (95% CL)	ICC (95% CL)	Reliability
Heel Slide	Flexion (°)	Text dominant	9.1 (5.9-21.5)	0.99 (0.87-1.00)	Extremely High
		Interactive graphic	2.5 (1.6-5.8)	1.00 (0.99-1.00)	Extremely High
	Extension (°)	Text dominant	9.1 (5.4-26.0)	0.97 (0.73-1.00)	Very High
		Interactive graphic	4.8 (3.1-11.3)	0.70 (-0.26-0.96)	Moderate
Sit to Stand	Flexion (°)	Text dominant	4.3 (2.6-12.5)	1.00 (0.99-1.00)	Extremely High
		Interactive graphic	3.9 (2.3-11.2)	0.99 (0.87-1.00)	Extremely High
	Extension (°)	Text dominant	5.2 (3.1-14.8)	0.99 (0.85-1.00)	Extremely High
		Interactive graphic	5.2 (3.1-14.9)	0.81 (0.01-0.98)	High

TE = Typical Error, ICC = Intraclass Correlation Coefficient, CL=Conference Limit, ICC magnitudes: ≥0.99 = extremely high, 0.90-0.99 = very high, 0.75-0.90 = high, 0.50-0.75 = moderate.

Discussion

The main aim of this study was to assess the reliability of the Digital Knee device; a secondary aim was to assess the influence of instruction presentation on sagittal plane knee movement reliability. Overall, the Digital Knee device was found to have very to extremely high reliability between sessions, with most flexion and extension recordings during the heel slide and sit to stand activities producing extremely high reliability coefficients. Generally, the within-session testing was found to have extremely high reliability across all protocols with all tests except for the interactive graphic group during the extension movement in the heel slide activity, which was found to have very high reliability. The findings were as expected as the device remained in the same place during the standardised exercises, therefore accepting the first research hypothesis.

Research specifically assessing the reliability of a single IMU sensor during a heel slide or sit to stand activity is minimal. However, reliability findings were similar (ICC = 0.85-0.96) to those reported by a previous study using multiple sensors to measure knee ROM (Kayaalp et al., 2019). The difference in TE across the text dominant and interactive graphic protocol were small, with the largest variation in typical error only 2.4° across all calculations. This is well within the range of error reported in previous research assessing a similar wearable sensor and comparing results to goniometer measures. Variation of up to 10° between measures of a digital device and a goniometer have been previously reported (Kumar et al., 2015). In addition, many studies have assessed the overall reliability of IMU measurements compared to video motion capture as a gold standard across a variety of movements, and deemed it to be a reliable method of recording movement (Di Paolo et al., 2021; Jaysrichai et al., 2015; Turner et al., 2021). This indicates the measurements recorded by the Digital Knee device are highly reliable within-session.

Between-session reliability was investigated alongside the within- session reliability as it is the most relevant to the device purpose (attaching the brace once a day for an extended period of time). Generally, the between-session testing was found to have very high to extremely high reliability. Two exceptions to this were found in the interactive graphic protocol group during the extension movement in both the heel slide and sit to stand activities. These movements were found to show moderate and high reliability respectively. The small number of participants used may have affected the results due to the reliability calculation method (Hopkins, 2000). From the results, a noticeable difference in TE was found in the between-session testing for the heel slide activity. The TE was much higher in the text dominant group for both the flexion and extension movements when compared to the interactive graphic protocol group. Additionally, the CL for the text dominant group in this condition were also much wider, denoting large variation of movement within this group. Despite the smaller TE and CL within the interactive graphic protocol group compared to the text dominant group, ICC values identified moderate reliability for the extension movement during the between-session analysis. We suspect that with a larger sample size the differences in reliability and typical error findings would be reduced. Furthermore, the effects of a small sample size were also apparent during the sit to stand activity. Both protocols for extension resulted in almost identical TE and CL however, ICC's for the text dominant protocol group (n=5) suggested extremely high reliability and for the interactive graphic protocol group (n=5) only highly reliability. Although ICC values were variable, assessing the reliability using the TE and CL indicates the interactive graphic protocol group was the more reliable instruction method. TE has been used as a reliability index in previous studies with smaller samples sizes, as it expresses the range of measurement error expected from repeated tests in the same units as the original measurement (Stratford & Goldsmith, 1997). This allows clear presentation of expected values from repeated tests and is thought to be more useful than ICC values with large CL ranges in small population studies (Stratford & Goldsmith, 1997).

One potential explanation for variation in the reliability results is user error, particularly with device placement and exercise technique/performance. Research has shown the placement of a movement sensor in a smart wearable can alter ROM recordings by around 10° (Marques et al., 2020). In this research participants were required to fit the brace independently regardless of assigned instruction protocol. This was done to mimic the telehealth aspect of such a device where participants would be required to fit the brace themselves. Future research comparing in-person fitment and independent remote fitment would be useful to determine the effects this has on ROM results. In attempt to reduce the influence of exercise technique on results, two simple exercise movements were selected for testing in a controlled environment. The sit to stand activity is a common activity of daily living, and the heel slide is relevant to a clinical population and therefore to the intended device user (Janssen et al., 2002). The movement during the sit to stand activity was relatively consistent throughout testing, which can be attributed to the commonality of the movement as well as the heel block used to standardise the exercise for repeated testing (Janssen et al., 2002). The heel slide activity was observed to be an unfamiliar task among the healthy population used. The test was standardised by using a block of wood for the participant to slide their heel against as a guide. One participant in the text dominant group did not maintain heel contact with the ground however during the rest time reviewed the instructions and corrected their movement for session two. The participant was excluded from data analysis during the between session analysis as their results largely swayed group results. These observations support the potential for user error having a major impact on the reliability of the knee motion measurements. However, the within-session results provide confidence that regardless of how the activity is performed if repeated within the same session the results will be similar.

The second study aim was to investigate if the reliability of the Digital Knee device could be improved through the addition of interactive graphic instruction. A secondary assessment compared the two instruction protocols for the placement, fitting and subsequent between-session reliability of the Digital Knee device. The text dominant protocol used text-based instructions while the interactive graphic protocol used an integrated approach of graphics accompanied by text. From the results there were no substantial differences in the reliability findings between the two instruction approaches, however, the difference in TE between the two protocols does suggest the interactive graphic protocol may be more reliable. The lower TE's for the interactive graphic protocol group is also accompanied by much narrower CL compared to the text dominant group, suggesting the digital group are more likely to get similar repeated results.

Based on subjective observation, the integrated approach may have also improved validity, however this was not assessed in this research. Future research using motion capture technology could assess the validity of the two protocols. Previous research has investigated the relationship between text and graphic instruction. The general consensus across the literature states instructions using both graphic and text is superior to text alone (Roy, 2006). The combination of text and graphic instruction has been found to help build mental models of the text based instructions (Glenberg & Langston, 1992), reduce processing speed for understanding (Wang et al., 2019), and facilitate faster learning of instructional assembly tasks (Beiger, 1982). This aligns with these research findings as similar results have been shown based on the observations during the testing period. Additionally, participants in the interactive graphic protocol group asked fewer questions during the testing period indicating they had greater understanding of the required task. Although the tester did not provide any assistance to support placement of the Digital Knee device, it is worth noting that participants in the interactive graphic protocol group were also observed to have improved device placement (more aligned with centre of kneecap as specified in the instructions) compared to the text dominant group, which aligns with the second hypothesis. The improved device placement is evidenced to be due to the better attention to instruction and faster learning as stated by Beiger (1982).

There were a few limitations present in this study. Firstly, although adequate wash-out time was ensured, between-session testing was performed on a single day which may not exactly replicate the use of a patient wearing this device on multiple days. Secondly, only a small number of participants were recruited due to the timing of COVID-19 lockdowns. Future research should look to assess both injured and uninjured participants within a larger sample size to assess differences and incorporate a familiarisation session of the activities (heel slide and sit to stand) to minimise a potential learning affect occurring between testing sessions.

Conclusion

Overall, the within-session reliability of knee ROM using the Digital Knee device was found to be extremely high under both tasks. Reliability varied during between-session testing to a greater extent than within-session testing, with findings showing moderate to extremely high reliability. No major differences were observed between the text dominant and interactive graphic instruction protocols. However, it was observed throughout testing, participants in the interactive graphic protocol group were better at following instructions and placing the device on their knee as suggested by the literature, providing support for the inclusion of interactive graphics within the device instructions. From these results it can be interpreted that the Digital Knee device can be used as a reliable tool to record ROM in both remote (telehealth) or in person rehabilitation settings, irrespective of instruction presentation.

Prelude to Chapter 4

The findings from the analysis of Digital Knee reliability are indicative of its suitability for use for rehab from a technical perspective, however there are further considerations regarding its feasibility to assist with ACL rehabilitation. Therefore Chapter 4 will investigate the influence the device can have on early-stage rehabilitation following ACLR through consideration of device accuracy over time and participant motivation and adherence during the rehabilitation process. The use of smart wearable devices is increasing among the medical community, with the shift to a more digitally integrated world. Smart wearable devices have been reported to have high levels of accuracy when compared to other measurement techniques such as video motion capture and goniometers. This chapter will compare early-stage rehabilitation measurements recorded using the Digital Knee to goniometer measures. To date no research has been conducted assessing the use of the Digital Knee during early stage ACLR rehabilitation, although previous research has reported benefits such as increased motivation and adherence when using other smart wearable devices. This chapter will further investigate the influence the Digital Knee has on motivation and adherence during rehabilitation.

Chapter 4: The Use of a Digital Knee device in Early-Stage Rehabilitation Post-Anterior Cruciate Ligament Reconstruction

Introduction

Wearable technology has made significant advancements since 2014, with reports stating 19% of Americans wear a smart watch or fitness tracker daily (Greiwe & Nyenhuis, 2020). It is assumed this prevalence is similar in New Zealand, however as more affordable devices are released this percentage is likely to increase. Increased commonality and use of smart wearables is supported by the ongoing effects of the global pandemic and a greater shift towards remote and digital healthcare. Additionally there is evidence to suggest the increased adoption of wearable technology is due to increased inquisition of personal data, as research has found users are drawn to devices which enable them to view snapshots of their performance (Greiwe & Nyenhuis, 2020).

A recently developed smart wearable is the Digital Knee device (OPUM 2021), designed to measure knee range of motion and general physical activity. The Digital knee is comprised of a unit containing an angle sensor and IMU (inertial movement sensor) which attach to the lateral side of a twin strap knee brace. The device is connected and controlled through the user's mobile phone. A vital aspect to the success of smart wearable devices as tools in healthcare is their accuracy in comparison with manual assessment made by a clinician. Confidence in remotely recorded measures made by smart wearables would enable clinicians to place a greater reliance on remote monitoring tools for healthcare as well as increase patient confidence in these remote tools. Some evidence suggests smart wearable devices such as the KneeHapp textile have a high level of accuracy (Faisal et al., 2020; Haladjian et al., 2018). Despite knee range of motion monitoring being one of the main functions of the Digital Knee no direct comparisons between clinical goniometer measures and Digital Knee measures have been completed.

A key feature of the Digital Knee which is similar to a goniometer is the ability to view measurement recordings immediately. The Digital Knee device enables users to view real time movement of their knee through a securely connected mobile application

(OPUM, 2021). Phone connectivity is a feature available in most smart wearable devices which enables users to easily set up and personalise their device. This not only increases usability of the device but also increases the accuracy of measures due to estimated limb length based on user height and sex (Huh et al., 2019). Through connection to a mobile application users of the digital knee can view real time knee motion angles, as well as view graphics to increase their understanding of the data (Wang et al., 2019). Real time feedback has been reported to assist in users adopting proactive health measures through increased understanding and empowerment (Greiwe & Nyenhuis, 2020). This proactive feature is suggested to be particularly useful during rehabilitation as it enables users to get quantitative feedback independently, potentially elevating patient motivation in between physiotherapy visits.

Standard practice during the first 6 weeks post ACL reconstruction involves weekly physiotherapy visits to monitor progress (Adams, Logerstedt, Hunter-Giordano, Axe, & Snyder-Mackler, 2012). Practitioners have previously reported smart wearable devices as useful tools during clinical decision making throughout these post-operative sessions (Haladjian et al., 2018), and as a tool to increase user exercise compliance (Greiwe & Nyenhuis, 2020). Compliance to rehabilitation exercises has been highlighted as a key area of concern by practitioners, with adherence to rehabilitation exercise programmes being reported as only 65% (Giggins et al., 2014). The constant monitoring available through smart wearables devices is suggested to add an increased level of responsibility to the individual and promote increased compliance to perform exercises (Ananthanarayan, Sheh, Chien, Profita, & Siek, 2013). This study aimed to investigate the usability of the Digital Knee during ACLR rehabilitation. The research will; (i) describe and compare sagittal plane knee ROM during ACL rehabilitation measured using a Digital Knee device and a goniometer, and (ii) investigate the impact of the Digital Knee on motivation and adherence during rehabilitation post ACL reconstruction.

Methods

Participants

A total of fifteen participants were recruited between the ages of 21 and 53 years. Eight participants formed the intervention group (using the Digital Knee device) with an average age of 41 ±11 years. Two participants in the intervention group also had knee flexion and extension measures recorded manually by a physiotherapist using a goniometer. Seven participants were retrospectively recruited to form the control group (all range of motion measures based on goniometry) with an average age of 25 ±3 years.. Seven intervention group participants participated in the individual semi structured interviews.

Eligibility

Individuals were eligible for selection in the control group if they were over 18 years of age, in their first two weeks post-surgery following a primary ACL reconstruction, with no other history of serious knee injury.

Individuals were eligible for inclusion within the intervention group if they were over the age of 18 years, were awaiting primary ACL reconstruction with no significant meniscal repair or were within four weeks post-surgery. To be eligible participants had to have no history of previous serious knee injury. Ethics approval was granted on the 6th of May 2021 under the reference 21/140.

Protocol

Deidentified control group data were collected from local physiotherapists. Physiotherapists provided data for participants who had surgery post June 2021, and for individuals who met the eligibility criteria. Participants' sex and date of birth were recorded in addition to weekly sagittal plane knee range of motion using a goniometer for the first 6 weeks post ACL reconstruction surgery.

Intervention group participants were recruited via local physiotherapists through the presentation of a study flyer. Individuals who expressed an interest were presented with the participant information sheet and consent form by the physiotherapist and given the opportunity to ask the physiotherapist questions. After the consent form had been signed the physiotherapist provided consented participants with a Digital Knee device. The researcher then collected the consent form and contacted the participant to set up a virtual meeting with the participant. During this meeting the participant had the opportunity to ask any further questions about the device, complete the health history survey, and to discuss the study requirements. During the virtual meeting the participant practiced fitting the Digital Knee device to their leg and connecting it to their phone. When connecting to the Digital Knee instructions were provided to participants via the OPUM lab mobile application via digital infographics.

All participants in the intervention group were required to complete a daily heel slide activity while wearing the Digital Knee and a weekly online progress survey through redcap software (P.A. Harris, 2008). To complete the heel slide activity the participants were asked to lay on their back and slide the heel of their braced leg along the floor towards and away from their buttock, aiming to reach maximum knee flexion and extension with each repetition. Three sets of fifteen repetitions were programmed into the heel slide activity on the OPUM application. Participants were also asked to wear the device as much as possible throughout the day to gain an indication of their activity level. Participants who were able to access a physiotherapist during their 6-week intervention period were asked to record range of motion results as measured by their physiotherapist (using a goniometer) on an additional redcap online form. The participants were all recruited through lockdown while only essential healthcare services were allowed, therefore manual range of motion testing was challenging to obtain. At the conclusion of the 6-week intervention, participants were invited to attend an individual online semi structured interview to provide feedback on the device. The interviews were conducted on Microsoft teams and key points were noted down. All participants were asked the same set of open-ended questions to establish key trends among participant responses. Seven out of eight participants agreed to participate in the interview.

Data Collection

Control group: Participant date of birth, sex and weekly maximum knee flexion and extension data were provided in a participant/physio electronic form. The weekly data was measured using a goniometer while the participant was supine and flexed their knee as far as possible followed by extending their leg as far as possible. Electronic data were transferred to an excel spread sheet for further processing. All control group data were obtained pre Covid-19 lockdown, when patients had full access to services such as physiotherapists and gyms.

Intervention group: Health history data as described in the eligibility section, was collected remotely via redcap survey software and downloaded as a CSV file. Flexion and extension data were collected daily through the OPUM web portal for each participant and recorded in an excel spreadsheet by the researcher. Missed days were recorded as blanks. An electronic weekly feedback form was completed at the end of each week asking the questions; how motivated are you to complete your weekly exercises (scale 0 – 10) and, do you feel like your knee has improved compared last week, how?. Once data collection had ceased feedback data were downloaded in a CSV file. The semi-structured individual participant interviews were completed post-intervention via a virtual Microsoft teams meeting. Written summary notes were recorded for each participant in response to the following open-ended questions.

1. How did you find your experience with the device and application?
2. What effect do you feel the digital knee had on your recovery?
3. Do you have any recommendations that could be made to the device based on your experiences?

Data Analysis:

Mean daily knee flexion and extension were calculated for the intervention group. Mean maximum weekly knee flexion/extension was additionally calculated based on the maximum daily flexion/extension measurements over each seven-day period. Control data was obtained for each control group participant as individual weekly measurements. Mean group maximum weekly flexion/extension was subsequently calculated. All control group participant data was included during mean group data analysis. Daily device use was calculated for each participant an averaged across the eight participants to calculate compliance.

Group mean weekly motivation scores were calculated for the intervention group through averaging out weekly feedback scores collected in the weekly questionnaire. Changes in motivation outcomes were considered in chronological order to reflect changes over time post-surgery. Common trends were identified throughout participant interview summary notes. Specifically, the interview notes were searched for mention of each identified trend and a tally was created to calculate the prevalence of each trend. Methodologies were limited to quantitative techniques for the analysis of the interview data however a summary table of key topic statements and their frequency of mention were displayed.

Results

During completion of the heel slide activity mean group knee flexion increased across the six-week period for the intervention group (Figure 6). The lowest mean knee flexion angle recorded was 53°±19 at day 7 and the maximum mean knee flexion angle recorded was 103°±8 at day 40. Individual knee flexion measures can be found in the appendix (Appendix B).

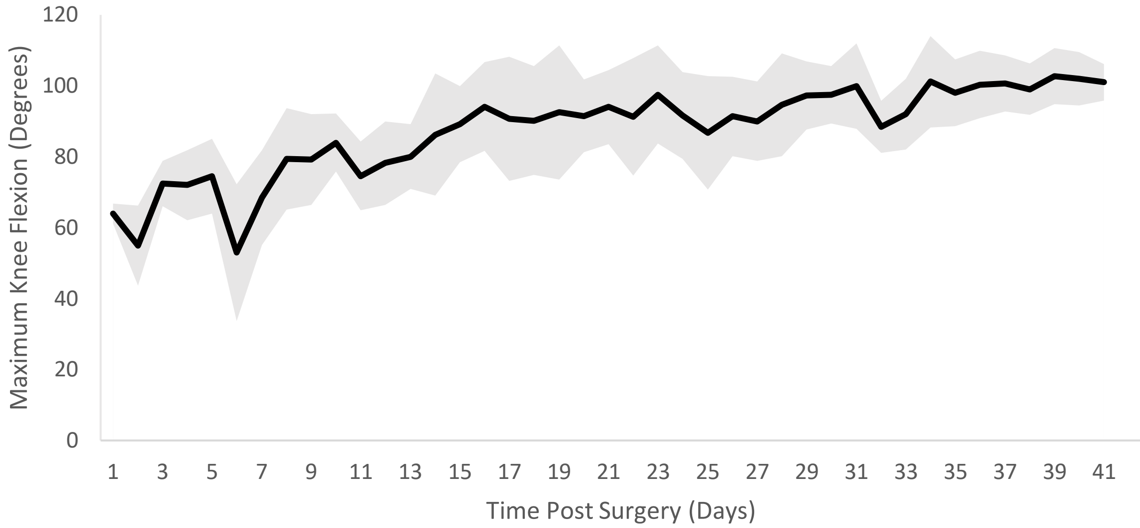

Figure 6: Mean (±SD) maximum daily knee flexion recorded via the Digital Knee during the heel slide activity.

The mean group sagittal plane knee angle never reached 0° (full knee extension) (Figure 7), however individual participants did record 0° or more knee extension on days 4, 21 and 23. The mean group knee extension ranged from -5° to 41°. Maximum mean extension was 6°±1 at day 6 and minimum mean extension was 24° ±13 at day 7. Individual knee extension measures can be found in the appendix (Appendix B). Comparison graphs between goniometer measurement and Digital Knee measurement groups can be found in the following figures.

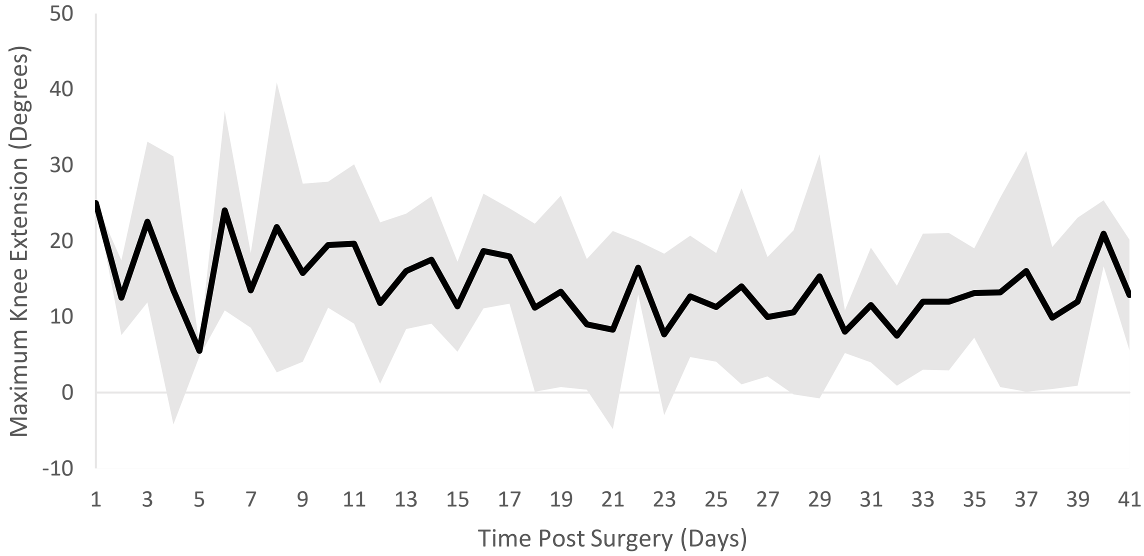

Figure 7: Mean (±SD) maximum daily knee extension recorded via the Digital Knee during the heel slide activity. (note zero degrees = full knee extension))

Mean weekly knee flexion for control group participants increased from 69°±11 to 119°±7 across the six week rehabilitation period (Figure 8) compared to the intervention group who experienced improvements from 69°±18 to 107°±5 over the same period of time (Figure 8). Both groups reported their highest measures of flexion in week six. Mean maximum knee extension angle continually decreased (improved extension) across both groups except for week six in the intervention group (Figure 9). Control group knee extension decreased from 11°±5 to 4°±2 after six weeks. The intervention group showed a decrease from 9°±11 to 4°±8 by week five and a slight increase at week six (6°±7) compared to week five.

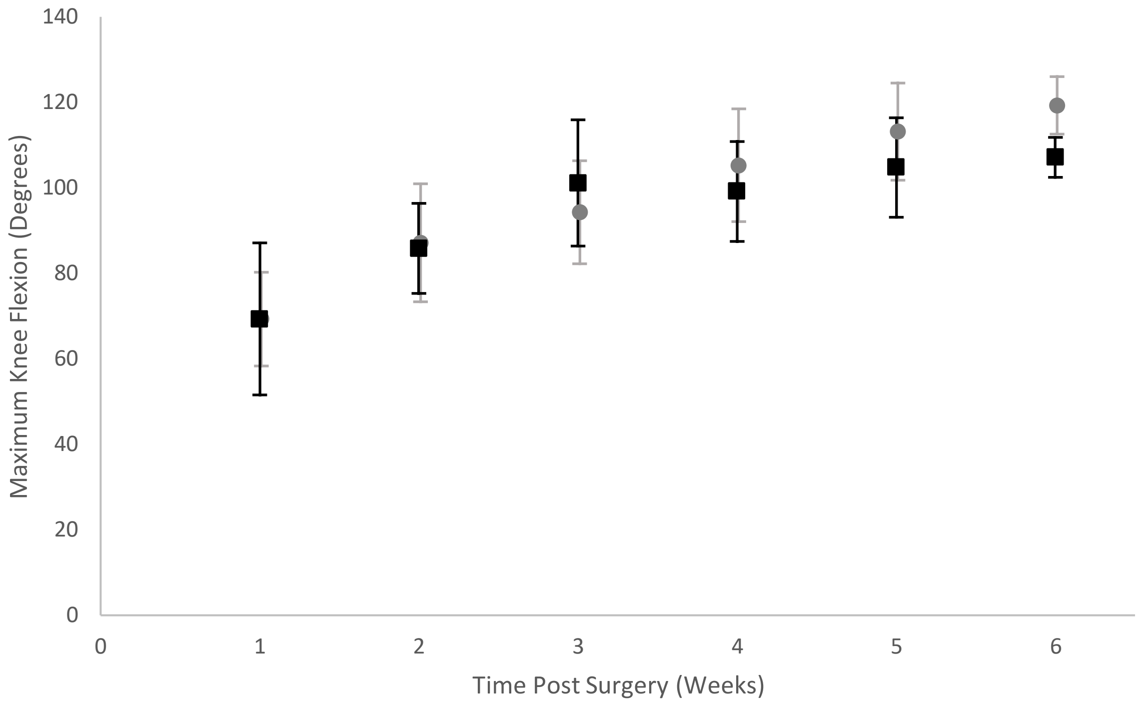

Figure 8: Mean (±SD) maximum weekly knee flexion recorded by the digital knee (squares) and goniometer (circles)

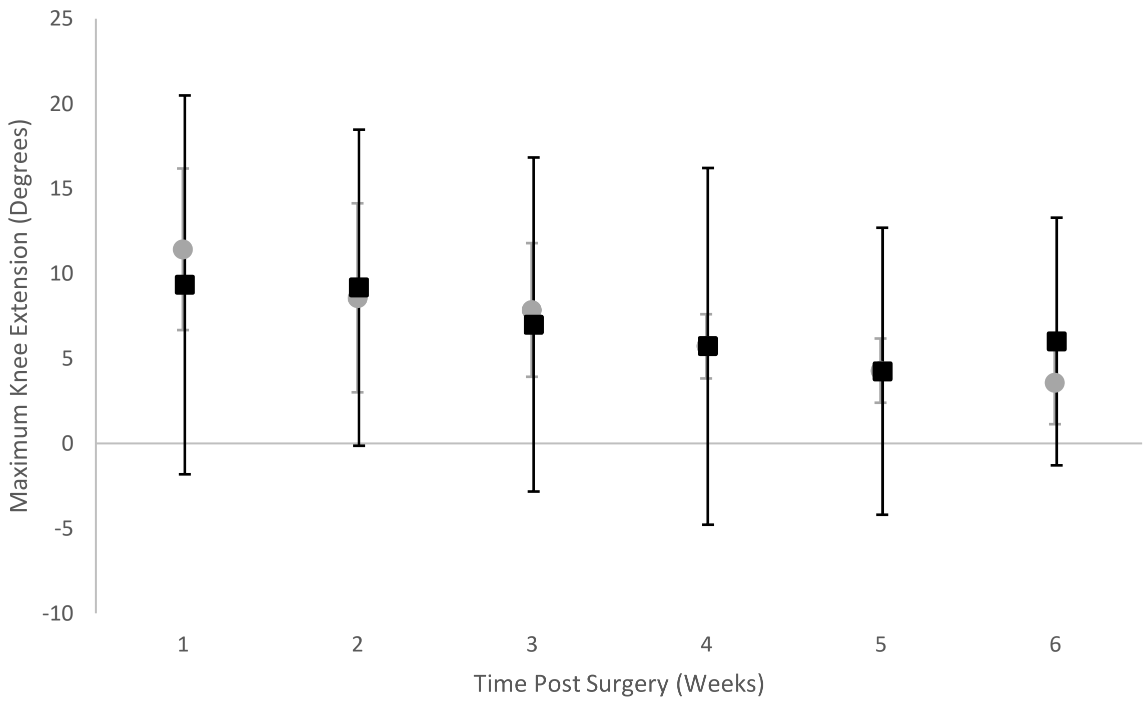

Figure 9: Mean (±SD) maximum weekly knee extension recorded by the digital knee (squares) and goniometer (circles). Note 0 degrees = full knee extension.

Overall motivation to complete exercises was observed to decrease over the six-week period within the intervention group. Motivation levels decreased from 95% in week one to 76% in week 6 (Figure 10). Average heel slide activity compliance using the Digital Knee was 79% (appendix B).

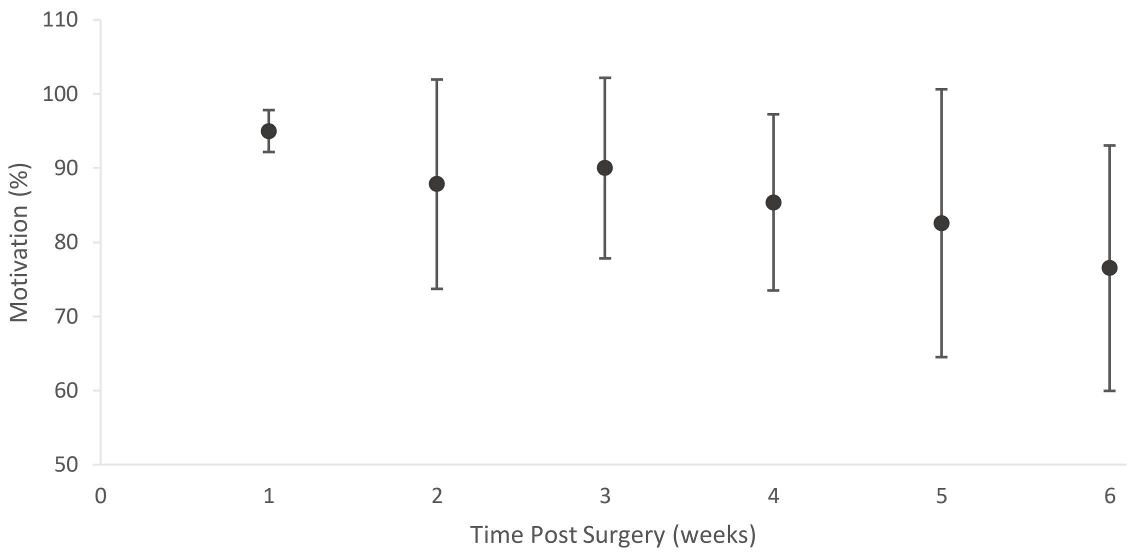

Figure 10: Weekly mean (±SD) motivation levels of intervention group participants to complete their exercises

During the semi-structured interview, comments regarding improved motivation and the graphic data display were the two most mentioned topics by participants in the intervention group (Table 5). All interviewed participants indicated the Digital Knee device helped with motivation at some point during the six weeks. Six out of seven participants suggested they found the device useful for their recovery, however the accuracy of measurements was a key concern for these participants who commented on inconsistencies with data recordings. Issues with connectivity and brace design were mentioned by five participants. Specific comments about clips breaking off the brace were mentioned by three participants, while comments about uncomfortably placed straps were made by two participants. Access to previously recorded data was mentioned by four of the participants, requesting the ability to see their own data clearly on the app once recorded. Six participants found the device useful for recovery however four sated the device could be significantly improved with a few small alterations such as access to historic data and improved accuracy and comfort.

Table 5: Summary of trends identified in semi structured interview. 7 out of 10 intervention participants who participated in the semi structured interviews

Trend	Prevalence of Trend (N)	Details
Motivation	7	All said the device helped with motivation at some point during the 6 weeks.
Connectivity	5	Five reported issues connecting to the device or staying connected to it during exercises.
Accuracy	6	Six participants mentioned recordings were not accurate particularly during full flexion, recalibration did not always fix the problem.
Brace Design	5	Three participants had broken the pop clips which connect to the straps to the brace. Two participants said the brace straps were uncomfortable.
Graphic Display	7	All liked the graphic display whilst they were doing the exercise. Five said they would like to be able to see a graphic all the time on the live data display screen (appendix B).
Historic Data Display	4	Four asked for the user interface to allow all user recorded data to be viewable on the app so they could better track their progress.
Useful	6	Found the device useful for their recovery. Four suggested the usability of the device could be improved with a few alterations

Discussion

This research sought to investigate the usability of the Digital Knee during rehabilitation by describing and comparing assessment of sagittal plane knee ROM between a Digital Knee device and a goniometer, and investigating the impact of the Digital Knee on motivation and adherence. Addressing the primary research aim of Chapter 4, daily ROM (knee flexion and extension) was remotely recorded on the Digital Knee device and showed weekly ROM improvements across the 6-week period for the intervention group. Increases in ROM were anticipated, as during the initial six week period post ACLR, there is generally a progressive reduction in knee swelling and inflammation, and an increase in knee mobility and neuromuscular control (Van Grinsven, Van Cingel, Holla, & Van Loon, 2010). Awareness of daily ROM progression could be useful for practitioners to allow greater insight into patient progress, and assist with scheduling follow up visits. Seven out of eight participants reported reaching 0° (full extension) during knee extension assessment via the digital knee within the six-weeks, but improvements in knee extension range were highly variable and inconsistent when analysed daily. To an extent this was expected as the deficits to knee extension post-surgery are not as pronounced as the deficits to knee flexion (Eckenrode et al., 2017). However, generally full extension compared to the uninvolved limb is expected to be consistently achieved by six weeks post ACLR to avoid long term gait deficits (Eckenrode et al., 2017). Additionally daily data was expected to vary slightly due to factors such as illness or increased activity (which can cause knee swelling), however device or user error could have also influenced the level of daily measurement variation. In consideration of these factors, weekly averages were used for data analysis to better evaluate the use of the device post ACLR and minimise the effect of daily fluctuations due to the small cohort of participants used. (Tripepi, Jager, Dekker, Wanner, & Zoccali, 2008).

Weekly Digital Knee ROM averages enabled direct comparisons with measurements taken using goniometers as per standard clinical practice. Initially these comparisons were planned to be performed on a single group of participants, however due to a Covid-19 lockdown two separate groups of participants were used (note: control group data was retrospectively collected from individuals who had surgery between June and August 2021). During early stage ACLR physiotherapists are recommended to have at least one session with their patient each week during which patient ROM is recorded to monitor patient progress (Adams et al., 2012). Typical knee flexion benchmarks post ACLR have been reported as around 90°, 100° and 120° after week one, two and three, respectively (Eckenrode et al., 2017). While similar improvements in knee flexion were evident across the six-week period for both groups, benchmarks were not achieved. Mean group knee flexion was also reported around 10° to 20° less than expected across weeks one to three for both control and intervention groups. Digital knee recorded maximal knee flexion was additionally reported to be lower than goniometer measures during weeks four to six.

Previously manual measurement error has been reported to be up to 10° which may explain the lower reported control group values (Patel et al., 2012). To reduce variability within control group data and improve measurement consistency all goniometer measurements were recorded by the same physiotherapist. The lower knee flexion recordings on the Digital Knee device, compared to goniometer measures, during weeks four to six could also be due to factors such as measurement/user error, or decreased quadriceps strength. Previous research has reported up to 25% of patients post ACLR do not achieve knee extension within 10° of the uninvolved limb by week four post operatically due to weakened quadriceps muscles (Adams et al., 2012). Quadriceps strengthening exercises are provided to patients pre and post ACLR to assist in regaining full knee function alongside stationary bike exercises (week 2 onwards) (Van Grinsven et al., 2010). However due to a COVID-19 lockdown the majority of the intervention group were unable to have access to standard rehabilitation practice which may have resulted in participants not understanding the importance of these exercises. This may also be a possible explanation for the variation in results between the measurement tools during weeks four to six, which otherwise were expected to be in line with goniometer recordings. Additionally, one participant noted in their weekly feedback questionnaire they had increased knee swelling for one week after receiving their COVID-19 vaccine. The impact of the vaccine on ACL rehabilitation has not been assessed however the participant noticed significantly less motion in their knee compared to the previous week, which would have reduced group mean knee flexion and extension.

The second aim of this study was to investigate the impact of the Digital Knee device on motivation during ACL rehabilitation. Motivation has been strongly linked to improved rehabilitation performance (Naeemabadi et al., 2020). All participants involved in the semi structured interviews identified the Digital Knee device to have helped with motivation. Although the baseline level of motivation reported was very high, this level slowly decreased throughout the 6-week period. It is speculated that use of the Digital Knee may have assisted to boost the initial motivation levels and possibly prolong the elevated levels in line with participant feedback. This aligns with previous research which has suggested that smart wearables prolong levels of motivation, however levels still decrease overtime (Ayoade & Baillie, 2014). Additionally Ayoade and Baillie (2014) also reported motivation was higher during post-surgical rehabilitation when compared to non-surgical rehabilitation, supporting the idea that the digital knee prolonged elevated motivation levels.

Another trend frequently mentioned during the semi structured interview was graphic data display. The Digital Knee device enabled participants to view a real time graphic of their knee motion during the completion of an exercise activity. This graphic was considered one of the most useful features of the device as participants were able to gain feedback on their movement and report this to their physiotherapist. However, suggestions were made by the participants to increase the availability of this feature to allow participants to view this data throughout the day via the data screen, similar to ability to view heart rate at any time on a smart watch (Huh et al., 2019). Based on participant feedback the addition of this feature to the device may assist in increased wear of the device during other activities such as squatting in the gym or daily walking, as it would allow an increased understanding of knee movement. Aligning with the suggested graphic development, previous research using a wearable device for ankles has reportedly increased commitment to training and improved movement through the ability to receive live feedback (Yeh et al., 2012). Participant use of the device beyond completion of the heel slide activity was minimal, however the Digital Knee device was suggested to be useful as a reminder to complete exercises. Additionally, compliance to complete the activity was relatively high. Previous research has reported high accountability can contribute to high compliance (Ananthanarayan et al., 2013). Several participants in the current study stated the daily activity kept them accountable as they were able to independently monitor their progress, as well as use the activity as a reminder to perform their additional physiotherapist prescribed rehabilitation exercises. Improved patient empowerment, enhanced error correction (via the live feedback feature) and improved engagement due to the effect of remote monitoring have been reported as a result of smart wearables in previous research (Correia et al., 2018). Aligning with our research findings, patients in a study by Correia et al. (2018) reported feeling accountable to do their exercises as they knew they were being monitored. Therefore, this increased accountability could be an advantage of the Digital Knee device, particularly in patients who struggle with maintaining motivation.

Further analysis of interview data contributed to the investigation into the usability of the Digital Knee device. Design of the device attachment technology was identified as a contributing factor to the finding of minimal use of the Digital Knee device beyond completion of their exercises. Based on participant feedback this is suggested to be because the design of the device attachment technology, as placement and calibration is crucial to the accuracy of the device (Haladjian et al., 2018). Although accuracy was not assessed, issues with brace design, e.g. strap placement and clips breaking, suggest the variability in knee angle measures could be attributed to variation in placement between sessions without re calibration prior to each wear (Haladjian et al., 2018). Improvements to the device hardware, for example revision of the clip design to a compression sleeve, would overcome the identified design issues as well as possibly increase daily wear due to improved comfort. An additional design feature commented on by participants was lack of access to an historical data display within the participant app interface. Participants suggested the device would have increased usability if they had the ability to track their progress and view all their recorded results. Access to historical data and constant viewable live feedback may increase the usability of the Digital Knee device as these are two of the most sought after features of smart wearables (Ananthanarayan et al., 2013; Haladjian et al., 2018). These features have been reported useful for both clinicians and patients to increase motivation and adherence to exercise (Argent, Slevin, et al., 2018). From this research OPUM (designers of the device) launched a new compression sleeve-based device to overcome the issues of comfort as well as misalignment. These modifications are thought to considerably improve the usability of the device, however future research should be conducted to evaluate the effects of the device design improvements.

Overall the research aims were fulfilled, however data collection challenges were introduced due to covid-19 and likely influenced the research outcomes to some extent. The ability to assess the direct impact of use of the Digital Knee device on motivation was hindered by the altered study design due to the covid-19 lockdown. Although research has shown video consultations are as effective as in person consultations (Fahey et al., 2021), factors such as participant camera set up, musculoskeletal knowledge and technical capabilities largely effected participant competence. Device placement was also difficult to view via a video call and placed heavy reliance on the participant feedback to ensure they were comfortable and the recordings looked representative of their knee angle. Additionally sudden changes in lockdown rules resulted in short notice for patient surgeries. This meant we were unable to get many of the devices to participants prior to their surgery to complete the induction and device fitting. Therefore, knee swelling may have impacted the participants ability to find bony prominences during the initial remote device alignment session as it had to occur post-surgery when their knee was swollen, increasing the likelihood of potential misalignment for the duration of their device use. This reinforces the need for an improved device attachment method, such as a compression sleeve style design, as the associated tighter fitment could improve issued identified such as device fitment error and comfort. During the semi structured interviews several participants noted Digital Knee measures did not seem reflective of the range of motion they felt they were achieving. After observation and partial analysis of the results, the research team had the opportunity to obtain weekly measures from a single participant taken from the Digital Knee and a physiotherapist (goniometer) on the same day. It was observed the Digital Knee recorded measures were between 8° and 22° lower than goniometer recorded measures on the same day (Appendix B). These observations align with participant feedback and recorded range of motion data. Additionally, from a conversation with the physiotherapist they suggested alteration to the attachment method of the device may improve accuracy due to tighter fitment at the knee. Brace design and historical data display findings have already contributed to the subsequent development of the Digital Knee device. Finally, from a researcher/clinician perspective analysing the data for daily wear was unable to be completed using the web portal due to a poor interface for retrieving detailed data, which questions the usability of recording this information. This suggests the device may not be suitable for daily activity tracking, however, it has shown to be promising as a remote measuring device with a few modifications.

Conclusion

Overall, the Digital Knee enhanced the ACLR rehabilitation experience. Similar average knee range of motion measures were recorded on the Digital Knee when compared to a goniometer however larger variation in measures were observed raising concerns over the accuracy of the device. The Digital Knee device helped participants maintain motivation and adherence to their rehabilitation exercises during the six-week period, through device features such as live data display. Participant recommendations were made to improve the comfort and user interface of the device to further improve its usability for early-stage rehabilitations post ACLR. These suggestions have been taken on board by the designers and have been incorporated into an upgraded version of the device.

Chapter 5: Discussion and Conclusion

Discussion

The overall aim of this research was to investigate the use of a Digital Knee device during rehabilitation post ACLR. Injury to the ACL requires surgical intervention and a lengthy rehabilitation period of six to nine months (Adams et al., 2012). Research suggests the first six weeks are the most crucial to regain symmetrical limb ROM post ACL reconstruction surgery and will often predict long term patient outcomes. Limb symmetry is usually tested using a goniometer during physiotherapy sessions, during which full knee flexion and knee extension is measured (Eckenrode et al., 2017). The Digital Knee is a smart wearable device proposed to combine the relevant features of a goniometer and motion capture measurement tools, to allow portable and remote knee motion measurement.

This research investigated the sagittal knee motion measurement of the Digital Knee device. Previous literature has found similar devices to exhibit a high level of reliability, however no consistent reporting technique of reliability findings were found. The overall reliability of the Digital Knee device during sagittal plane knee flexion and extension was found to be very high for both between and within session conditions (ICC=0.70 – 1.0). Slightly larger variability was observed under the between condition measures, however this was expected due to the device being physically removed and re-attached. Digital Knee device placement is a recognised source of error, therefore as part of the reliability assessment two varied instruction protocols were trialled (text dominant and infographic digital dominant). The two instruction protocols did not influence the reliability of the device however from observation it was noted participants had better placement and compliance to instruction under the infographic dominant protocol. This observation is supported by the literature, with reports suggesting infographics enable faster learning and better understanding compared to text dominant instruction (Beiger, 1982; Wang et al., 2019). While use of the text dominant instruction protocol appeared to be sufficient for this reliability research, difference between the two instruction protocols may have been notable in knee ROM accuracy. Therefore, the use of infographics in device setup was carried through to the main study in this thesis. Although the accuracy of the Digital Knee device was not assessed in this research, it is recommended future research investigates the relationship between goniometer and Digital Knee recorded knee motion. Nevertheless, the device was observed to remotely record average weekly knee flexion and extension within similar range to goniometer recorded knee motion measures. This suggests that further research is required to build on this observational research which appears encouraging for the use of the Digital Knee as a rehabilitation tool.

A secondary focus area of this research was assessing the effect of the Digital Knee device on motivation and adherence, as previous literature has suggested individuals are more driven to perform exercise at home if they have the ability to view live feedback during the session (De Benedictis et al., 2020). The Digital Knee device enabled users to visualise their knee range of motion daily during their prescribed heal slide activity. It was reported this feature supported participants during their rehabilitation period to comply with their rehabilitation exercises as they were able to independently monitor their progress. Additionally, the Digital Knee has the ability to save recorded data to the online web portal, which is accessible by both the researcher and their approved clinician if requested, creating a feeling of accountability and further motivating individuals to adhere to their rehabilitation programme. Although the live graphic display was advocated to help with motivation during the rehabilitation period, participants suggested improving the accessibility of this feature. Participants suggested an improvement within the live graphic functionality to enable viewing of this graphic at any time when the device is connected to the mobile application. Another suggestion made by participants after using the device for six weeks was to improve the hardware of the device. The Digital Knee was attached to the knee using two elastic Velcro straps below and above the knee. Participants reported these straps to be uncomfortable particularly during the first few weeks due to swelling and bruising. Recently there has been increased development in soft textiles to improve the comfort of smart wearable sensors (Gupta et al., 2021). To improve the concern of comfort highlighted in this research OPUM have launched a compression sleeve-based soft textile design of the Digital Knee device. From this research OPUM have also improved the app interface to enable full time view of the live graphic display (Appendix B) as suggested by the research participants.

Limitations and Future Research

There were several limitations to this research which should be considered when interpreting the results. Suggestions for further research have been provided based on the research outcomes and limitations.

The small sample size used in chapter 4 was a limiting factor which is often unavoidable working with human participants particularly post ACLR. Additionally, covid -19 played a large role in participant recruitment and data collection for chapter 4 as this occurred during a four-month long lockdown. Furthermore, the number of ACL injuries reduced due to cancellation of all sports, drastically reducing the number of required reconstruction surgeries. Future research should look to incorporate larger sample sizes to increase the confidence and strength of the findings in both chapters 3 and 4.

The covid-19 lockdown also required a number of changes to be made to the research methodology. Participant inductions were changed from in person to virtual making it difficult to ensure correct placement of the device. Future research should use a trained professional to teach participants how to attach the device before allowing them to use it remotely, as this could improve the accuracy of device measures. Using trained professionals to train patients could however be avoided with an introduction of an improved and more user friendly attachment design, such as a compression sleeve or compression strap. Additionally, pre surgery participant recruitment was made more difficult due surgeries being booked at short notice once they were able to resume. This meant the majority of the participants were recruited during their 1-week post-surgery follow up, limiting the amount of data available to be collected from week 1. Future research should look to investigate use of the digital knee from day 1 post operatively. This research also highlighted the high variability in day to day results and should perhaps look to consider the frequency of progress measurements to weekly. Finally goniometer measurement recordings were limited as the majority of participants were still unable to attend in person physiotherapy appointments. This meant we were unable to compare the accuracy of the Digital Knee recorded measures compared to goniometer recorded measures. Future research should look to compare measurement recordings using both tools to allow analysis of the device accuracy in practice to occur. Conducting future research in this way will also account for natural improvements in ROM, and detail how the Digital Knee may accelerate ROM at variable post-operative time points.

Practical applications

The digital knee appears to be reliable in both between and within condition reliability testing and thus it has potential for increased clinical use, however the accuracy of the device is unknown. The Digital Knee likely encourages motivation and adherence to rehabilitation exercises post-ACLR. OPUM have made improvements to the hardware and software components of the Digital Knee device from these research findings, improving the overall usability of the Digital Knee.

Conclusion

Overall, the Digital Knee is a new and exciting smart wearable device with promising potential as a rehabilitation tool. Previous research has highlighted the benefits of smart wearable devices, with similar benefits to motivation observed in this research. Use of the Digital Knee has been suggested to prolong heightened levels of motivation post-surgery and increase compliance to exercises due to the live feedback. The reliability of the device was also found to be good during repeated testing. Through the findings of this research OPUM were able to further develop the Digital Knee device to improve user experience. Future research should be undertaken to update the current study findings as well as assess the accuracy of the device, and further the development of the Digital Knee as an assistive rehabilitation tool post-ACL reconstruction surgery. Finally to best integrate the Digital Knee device into practice, OPUM should consider collaborating with the ACC. This would assist in alleviating some cost barriers associated with new technologies, as well as increase the exposure of clinicians to the device.

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Watanabe, T., & Saito, H. (2011, 30 Aug.-3 Sept. 2011). Tests of wireless wearable sensor system in joint angle measurement of lower limbs Symposium conducted at the meeting of the 2011 Annual International Conference of the

IEEE Engineering in Medicine and Biology Society https://doi.org/10.1109/IEMBS.2011.6091395

Weinberg, B., Nikitczuk, J., Patel, S., Patritti, B., Mavroidis, C., Bonato, P., & Canavan, P. (2007). Design, control and human testing of an active knee rehabilitation orthotic device*IEEE.* Symposium conducted at the meeting of the Proceedings 2007 IEEE International Conference on Robotics and Automation

Whelan, D. F., O'Reilly, M. A., Ward, T. E., Delahunt, E., & Caulfield, B. (2017). Technology in rehabilitation: evaluating the single leg squat exercise with wearable inertial measurement units. *Methods of information in medicine, 56*(02), 88-94.

Yeh, S.-C., Chang, S.-M., Chen, S.-Y., Hwang, W.-Y., Huang, T.-C., & Tsai, T.-L. (2012). A lower limb fracture postoperative-guided interactive rehabilitation training system and its effectiveness analysis*IEEE.* Symposium conducted at the meeting of the 2012 IEEE 14th International Conference on e-Health Networking, Applications and Services (Healthcom)

Appendix

Appendix A

AUT
TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

6 May 2021

Hannah Wyatt
Faculty of Health and Environmental Sciences

Dear Hannah

Ethics Application: 21/140 Functionality of a digital knee device

Thank you for submitting your application for ethical review. We are pleased to advise that the Auckland University of Technology Ethics Committee (AUTEC) approved your ethics application in stages at their meeting on 17 May 2021, subject to:

1. Clarification of what will happen if Part A reveals that the digital knee device is not reliable;
2. Reconsideration of the use of the term 'knee brace' given that it appears to lack a locking mechanism. AUTEC suggests that 'digital knee device', used in the early part of the EA1, may be more accurate. Ensure consistent use of the appropriate term throughout the public-facing documents;
3. Justification for the storage of data from Part A on University of Auckland servers as noted in B.12;
4. Amendment of the Information Sheet as follows:
   a. Disclosure of the funder;
   b. Inclusion of advice about OPUM;
   c. Inclusion in the 'what will happen' section of a brief overview of the whole project so that participants have a sense of how their contribution fits in;
   d. Inclusion in the 'what will happen' section of more information about the app participants will engage with in Part A and how they will access this i.e. via their own smart phone or one that will be provided to them as noted in I.1.4;
   e. Update 'accuracy' in the benefits section to 'reliability' as in this research there is no comparison to a gold standard;
   f. Inclusion of the names and institutional affiliations of both supervisors in the privacy section;
   g. Inclusion of clear advice about the sharing of data;
5. Reword the bullet point about data sharing in the Consent Form so that it is clear that participants can choose whether or not their data will be shared with Opum;
6. Clarification of the time required in Part A; the Information Sheet says 90 minutes but I.1.2 says 2 hours. Update the Information Sheet as appropriate;
7. Inclusion of the title of the research on the recruitment advertisement for participants in Part A;
8. Provision of the authorising signature in O.3;
9. Clarification of whether data will be stored for 6 years (H.9.1) or 10 years (H.9);

10. Provision of an assurance that supervisors' students, and patients of the researcher, will be excluded from participation. Inclusion of advice about this in the Information Sheet and the advertisement for Part A.

This approval is for the assessment of measurement reliability stage only. Full information about each subsequent stage needs to be provided to and approved by AUTEC before recruitment for that stage commences and data is collected.

Please provide us with a response to the points raised in these conditions, indicating either how you have satisfied these points or proposing an alternative approach. AUTEC also requires copies of any altered documents, such as Information Sheets, surveys etc. You are not required to resubmit the application form again. Any changes to responses in the form required by the committee in their conditions may be included in a supporting memorandum.

Please note that the Committee is always willing to discuss with applicants the points that have been made. There may be information that has not been made available to the Committee, or aspects of the research may not have been fully understood.

Once your response is received and confirmed as satisfying the Committee's points, you will be notified of the full approval of your ethics application. Full approval is not effective until all the conditions have been met. Data collection may not commence until full approval has been confirmed. If these conditions are not met within six months, your application may be closed and a new application will be required if you wish to continue with this research.

To enable us to provide you with efficient service, we ask that you use the application number and study title in all correspondence with us. If you have any enquiries about this application, or anything else, please do contact us at ethics@aut.ac.nz.

We look forward to hearing from you,

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: Anja.vangulden@gmail.com; chris.whatman@aut.ac.nz

Appendix B

a) Summary of reviewed articles

Table 6: Summary of all reviewed articles used for the chapter to systematic review

Author and Date	Title	Telehealth Assessed?	Wearable Device Used?
Turner, A. J., Carroll, W., Kodithuwakku Arachchige, S. N., Saucier, D., Burch V, R. F., Ball, J. E., . . . Chander, H. (2021)	Closing the Wearable Gap—Part VIII: A Validation Study for a Smart Knee Brace to Capture Knee Joint Kinematics	No	Yes
Argent, R., Daly, A., & Caulfield, B. (2018)	Patient involvement with home-based exercise programs: can connected health interventions influence adherence	Yes	No
Dunphy, E., & Gardner, E. C. (2020)	Telerehabilitation to Address the rehabilitation gap in anterior cruciate ligament care: Survey of patients	Yes	Yes
Naeemabadi, M., Søndergaard, J. H., Klastrup, A., Schlünsen, A. P., Lauritsen, R. E. K., Hansen, J., . . . Kim, K. K. (2020)	Development of an individualized asynchronous sensor-based telerehabilitation program for patients undergoing total knee replacement: Participatory design.	Yes	Yes
Haladjian, J., Bredies, K., & Bruegge, B. (2018)	KneeHapp textile: A smart textile system for rehabilitation of knee injuries	Yes	Yes
Porciuncula, F., Roto, A. V., Kumar, D., Davis, I., Roy, S., Walsh, C. J., & Awad, L. N. (2018)	Wearable movement sensors for rehabilitation: a focused review of technological and clinical advances	No	Yes
Poitras, I., Dupuis, F., Bielmann, M., Campeau-Lecours, A., Mercier, C., Bouyer, L. J., & Roy, J.-S. (2019)	Validity and reliability of wearable sensors for joint angle estimation: A systematic review	No	Yes

Kumar, Y., Yen, S.-C., Tay, A., Lee, W., Gao, F., Zhao, Z., . . . Koh, G. (2015)	Wireless wearable range-of-motion sensor system for upper and lower extremity joints: a validation study	No	Yes
Jaysrichai, T., Suputtitada, A., & Khovidhungij, W. (2015)	Mobile Sensor Application for Kinematic Detection of the Knees		Yes
Kayaalp, M. E., Agres, A. N., Reichmann, J., Bashkuev, M., Duda, G. N., & Becker, R. (2019)	Validation of a novel device for the knee monitoring of orthopaedic patients	Yes	Yes
Giggins, O. M., Sweeney, K. T., & Caulfield, B. (2014)	Rehabilitation exercise assessment using inertial sensors: a cross-sectional analytical study	No	Yes
Argent, R., Slevin, P., Bevilacqua, A., Neligan, M., Daly, A., & Caulfield, B. (2018)	Clinician perceptions of a prototype wearable exercise biofeedback system for orthopaedic rehabilitation: a qualitative exploration		Yes
Faisal, A. I., Majumder, S., Scott, R., Mondal, T., Cowan, D., & Deen, M. J. (2020)	A simple, low-cost multi-sensor-based smart wearable knee monitoring system.	No	Yes
Di Paolo, S., Lopomo, N. F., Della Villa, F., Paolini, G., Figari, G., Bragonzoni, L., . . . Zaffagnini, S. (2021)	Rehabilitation and Return to Sport Assessment after Anterior Cruciate Ligament Injury: Quantifying Joint Kinematics during Complex High-Speed Tasks through Wearable Sensors	No	Yes
Ianculescu, M., Andrei, B., & Alexandru, A. (2019)	A smart assistance solution for remotely monitoring the orthopaedic rehabilitation process using wearable technology: Re. flex system	Yes	Yes
Ayoade, M., & Baillie, L. (2014)	A novel knee rehabilitation system for the home Symposium	Yes	Yes
Anthonius Lim, M., & Pranata, R. (2020)	Letter to the editor regarding ‘The challenging battle of mankind against COVID-19 outbreak: Is this global international biological catastrophe the beginning of a new era?’–Is telehealth the future of orthopaedic and rehabilitation in post-COVID-19 era?	Yes	No

Fahey, E., Elsheikh, M. F., Davey, M. S., Rowan, F., Cassidy, J. T., & Cleary, M. S. (2021)	Telemedicine in Orthopedic Surgery: A Systematic Review of Current Evidence	Yes	No
Kane, L. T., Thakar, O., Jamgochian, G., Lazarus, M. D., Abboud, J. A., Namdari, S., & Horneff, J. G. (2020)	The role of telehealth as a platform for postoperative visits following rotator cuff repair: a prospective, randomized controlled trial	Yes	No
Phuphanich, M. E., Sinha, K. R., Truong, M., & Pham, Q. G. (2021)	Telemedicine for Musculoskeletal Rehabilitation and Orthopedic Postoperative Rehabilitation	Yes	Yes
Perez, A. J., & Zeadally, S. (2017)	Privacy issues and solutions for consumer wearables. *It Professional, 20*(4), 46-56	No	No
Tousignant, M., Moffet, H., Boissy, P., Corriveau, H., Cabana, F., & Marquis, F. (2011)	A randomized controlled trial of home telerehabilitation for post-knee arthroplasty	Yes	No
Whelan, D. F., O'Reilly, M. A., Ward, T. E., Delahunt, E., & Caulfield, B. (2017)	Technology in rehabilitation: evaluating the single leg squat exercise with wearable inertial measurement units.	No	Yes
Chapman, R. M., Moschetti, W. E., & Van Citters, D. W. (2021)	Is clinically measured knee range of motion after total knee arthroplasty ‘good enough?’: A feasibility study using wearable inertial measurement units to compare knee range of motion captured during physical therapy versus at home	No	Yes

b) Text dominant instruction protocol

The Effectiveness of the Digital Knee Part 1

What will I be doing?

In this testing session you will be completing 2 exercises

1. Heel slide
2. Sit to stand (without arm support)

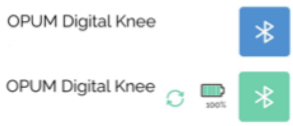
Each exercise will be performed whilst wearing the digital knee on your left knee. Instructions on how to perform the exercises can be found below. Each exercise will be completed for 4 repetitions and maximum and minimum results recorded. You will then repeat the same exercise. Following this you will complete the second exercise for 4 repetitions and record maximum and minimum results. You will then repeat this exercise for a second time and record results. You will then be able to remove the brace and rest for 15 minutes. After this you will reattach the brace and repeat the above steps.

Please read through ALL instructions before beginning and remove your shoes to complete the heel slide activity.

Reliability Study Protocol

Connecting to your device

1. Turn on knee brace by pressing and holding the central button and open the OPUM application.
2. Log in with the details provided to you.
3. Go into OPUM Lab “settings” tab and select “Connect my device”. Available Devices will be listed. Refresh the screen if needed.
4. If this is the first time connecting your device , press the button on your digital knee to enable bonding, LED will flash **blue** (security measure to ensure you are the only one that can connect to your device).
5. Tap the **Blue** Bluetooth icon of the device in OPUM Lab.
6. When the icon turns **green** you are fully connected.



Calibrate the device

1. Connect the rechargeable device to the side of the knee brace.
2. On the settings screen tap on the “Digital knee settings”
3. In the dialog box and ensure the correct leg is ticked.
4. Hold the knee brace in an upright position firmly holding the hinge completely straight.
5. Return to the device info dialog screen and tap calibrate. Then press “start recording data”
6. Turn the device off using the centre button the device will automatically disconnect. Turn the device back on and follow the following steps.

How to attach the brace.

1. Attach the Brace to your leg by adjusting the Velcro straps. Place your knee in a comfortable position whilst sitting on a chair.
2. Place the device on the outside (lateral) of your knee and align the release button with the middle of your kneecap.

3. Once this is aligned place your hand on the side of the brace and tighten the lower leg strap. This should be firm but comfortable (you should be able to place one finger under the strap while sitting down).
4. Repeat step 3 and attach the top strap.
5. Bend and straighten your knee a few times to ensure the placement feels comfortable.

Testing the brace.

1. With the brace attached to your leg got to the setting tab and tap “go to live session”
2. Bend and straighten your leg. The screen should change to show different degrees for each heading as you move. If this is the case, go to the completing activity section below. *Note: if the device is not showing live data movement at the beginning of an exercise complete step 3 and then return to the activity*
3. If the device is not recording movement, please reset it by turning it off and on again and check it is connected. Test the brace again following the above 2 steps.

Completing the activity

1. Go to the activities tab in OPUM App.
2. Select the desired activity (both activities need to be completed)
    a. Heel slide activity – Lie comfortably on your back and bend your knee towards you by sliding your heel along the floor, then straighten the knee back to starting position (as shown in video). During the exercises keep your heel in line with the floor marking (wooden plank). Once you are ready to begin place your knee in a slightly bent position and start the activity.

    b. Sit to stand without arm support activity – Before starting the activity sit on the chair and ensure your heels are pressed firmly against the heel block. This is to ensure your feet do not move during the exercise. Reach out with your arms and lean forward at your hips until your bottom starts to lift off the chair. Move your body into a standing upright position. Make sure not to let your knee collapse inwards during this exercise.

3. Watch the video in the OPUM App and read through the instructions on how to perform the activity.
4. Once you are ready to begin the activity tap “start”
5. A Live time graphic will appear on the app to display your movements.
6. Once you finish the activity tap “I’m done”.
7. A green tick will appear on the activity to indicate it has been completed.
8. The researcher will record your results and you may start the next activity. To do this press on the small arrow in the bottom right corner of the screen.
9. Repeat the same activity again. Progress to the sit to stand activity.
10. Complete this activity twice then remove the brace and rest for 15 minutes. Close the activity by pressing the close button at the bottom centre of the screen. After this you may re attach the brace and complete both activities twice more each. (Below is an example of the order in which you should complete your activities).

Order of Activities

1. Perform Heel slide activity (1 set of 4 repetitions)
2. Perform Heel slide activity (1 set of 4 repetitions)
3. Perform Sit to stand with arms unsupported activity (1 set of 4 repetitions)
4. Perform Sit to stand with arms unsupported activity (1 set of 4 repetitions)
5. Rest 15 Minutes
6. Perform Heel slide activity (1 set of 4 repetitions)
7. Perform Heel slide activity (1 set of 4 repetitions)
8. Perform Sit to stand with arms unsupported activity (1 set of 4 repetitions)
9. Perform Sit to stand with arms unsupported activity (1 set of 4 repetitions)
10. You have completed testing!

Note: Ensure you have seen/completed the following paperwork

1. Consent Form + Participant Information Sheet
2. Health History Questionnaire

c) Interactive graphic instruction protocol

The Effectiveness of the Digital Knee Part 1

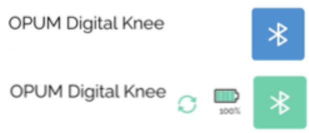
What will I be doing?
In this testing session you will be completing 2 exercises
1. Heel slide
2. Sit to stand (without arm support)

Each exercise will be performed whilst wearing the digital knee on your left knee. Instructions on how to perform the exercises can be found below. Each exercise will be completed for 4 repetitions and maximum and minimum results recorded. You will then repeat the same exercise. Following this you will complete the second exercise for 4 repetitions and record maximum and minimum results. You will then repeat this exercise for a second time and record results. You will then be able to remove the brace and rest for 15 minutes. After this you will reattach the brace and repeat the above steps.

Please read through ALL instructions before beginning and remove your shoes to complete the heel slide activity.

Reliability Study Protocol

Connecting to your device
1. Turn on knee brace by pressing and holding the central button and open the OPUM application.
2. Log in with the details provided to you.
3. Go into OPUM Lab "settings" tab and select "Connect my device". Available Devices will be listed. Refresh the screen if needed.
4. If this is the first time connecting your device , press the button on your digital knee to enable bonding, LED will flash **blue** (security measure to ensure you are the only one that can connect to your device).
5. Tap the **Blue** Bluetooth icon of the device in OPUM Lab.
6. When the icon turns **green** you are fully connected.



Calibrate the device
1. Connect the rechargeable device to the side of the knee brace.
2. On the settings screen tap on the "Digital knee settings"
3. In the dialog box and ensure the correct leg is ticked.
4. Hold the knee brace in an upright position firmly holding the hinge completely straight.
5. Return to the device info dialog screen and tap calibrate. Then press "start recording data"
6. Turn the device off using the centre button the device will automatically disconnect. Turn the device back on and follow the following steps.

Testing the brace.
1. With the brace attached to your leg got to the setting tab and tap "go to live session"
2. Bend and straighten your leg. The screen should change to show different degrees for each heading as you move. If this is the case, go to the completing activity section

below. *Note: if the device is not showing live data movement at the beginning of an exercise complete step 3 and then return to the activity*
3. If the device is not recording movement, please reset it by turning it off and on again and check it is connected. Test the brace again following the above 2 steps.

How to attach the brace and complete the activities.

1. In the activities tab along the bottom of your screen press on the day 1 instruction activity
2. Carefully read and follow the instructions.
3. Once you have completed the Day 1 activity, all following activities will follow.
4. Ensure you complete the activity as stated by the Heel Slide Instruction and Sit to Stand Instruction activities. Take note of the starting positions for each as noted on the instruction sheet.
5. Let the researcher know each time you start and finish and activity.
6. Once you are ready to begin the activity tap "start"
7. A Live time graphic will appear on the app to display your movements.
8. Once you finish the activity tap "I'm done".
9. A green tick will appear on the activity to indicate it has been completed.
10. The researcher will record your results and you may start the next activity. To do this press on the small arrow in the bottom right corner of the screen.
11. Repeat the same activity again. Progress to the sit to stand activity.
12. Complete this activity twice then remove the brace and rest for 15 minutes. Close the activity by pressing the close button at the bottom centre of the screen. After this you may re attach the brace and complete both activities twice more each. (Below is an example of the order in which you should complete your activities).

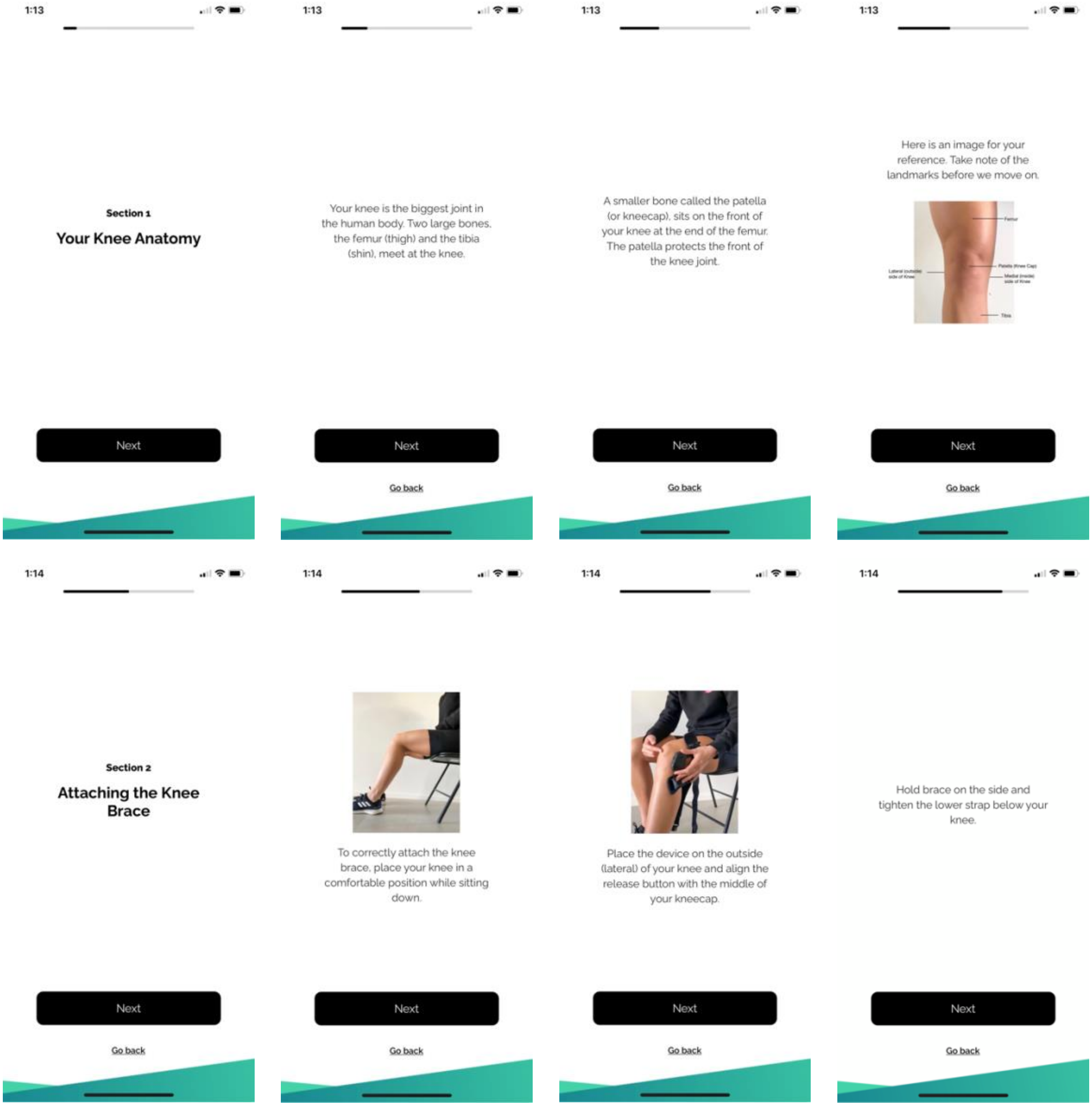
    1. Read Day 1 – Getting started Instructions
    2. Read Heel Slide Activity Instructions
    3. Perform Heel slide activity (1 set of 4 repetitions)
    4. Perform Heel slide activity (1 set of 4 repetitions)
    5. Read Sit to stand Activity Instructions
    6. Perform Sit to stand with arms unsupported activity (1 set of 4 repetitions)
    7. Perform Sit to stand with arms unsupported activity (1 set of 4 repetitions)
    8. Rest 15 Minutes
    9. Perform Heel slide activity (1 set of 4 repetitions)
    10. Perform Heel slide activity (1 set of 4 repetitions)
    11. Perform Sit to stand with arms unsupported activity (1 set of 4 repetitions)
    12. Perform Sit to stand with arms unsupported activity (1 set of 4 repetitions)
    13. You have completed testing!

Note: Ensure you have seen/completed the following paperwork

3. Consent Form + Participant Information Sheet
4. Health History Questionnaire

d) Interactive graphic instruction protocol delivery via the OPUM Lab application

Table 7: Interactive graphic instruction protocol viewed on the OPUM Lab mobile application



1:14

Tighten the top strap. Bend and straighten knee to ensure the strap is firm but comfortable. You should be able to place one finger under the strap while sitting down.

Next

Go back

1:14

All done. Your brace should now be correctly attached.

Done

Go back

1:15

Heel Slide Instructions

Next

1:15

Lie comfortably on your back and bend your knee towards you by sliding your heel along the floor, then straighten the knee back to starting position

Next

Go back

1:15

Lie comfortably on your back and bend your knee towards you by sliding your heel along the floor, then straighten the knee back to starting position

Next

Go back

1:15

During the exercises keep your heel in line with the floor marking.

Next

Go back

1:15

Once you are ready to begin place your knee in a slightly bent position and tap start activity.

Done

Go back

1:15

Sit to Stand

Without Arm Support

Next

1:15

Before starting the activity sit on the chair and ensure your heels are pressed firmly against the heel block, toes pointing forward and arms extended Infront of you. This is to ensure your feet do not move during the exercise.

Next

Go back

1:16

Reach out with your arms and lean forward at your hips until your bottom starts to lift off the chair. Move your body into a standing upright position.

Next

Go back

1:16

You may now press start the activity and then sit back down on the chair. Continue to perform the sit to stand activity for the specified repetitions.

Next

Go back

1:16

Make sure not to let your knee collapse inwards during this exercise.

Done

Go back

e)

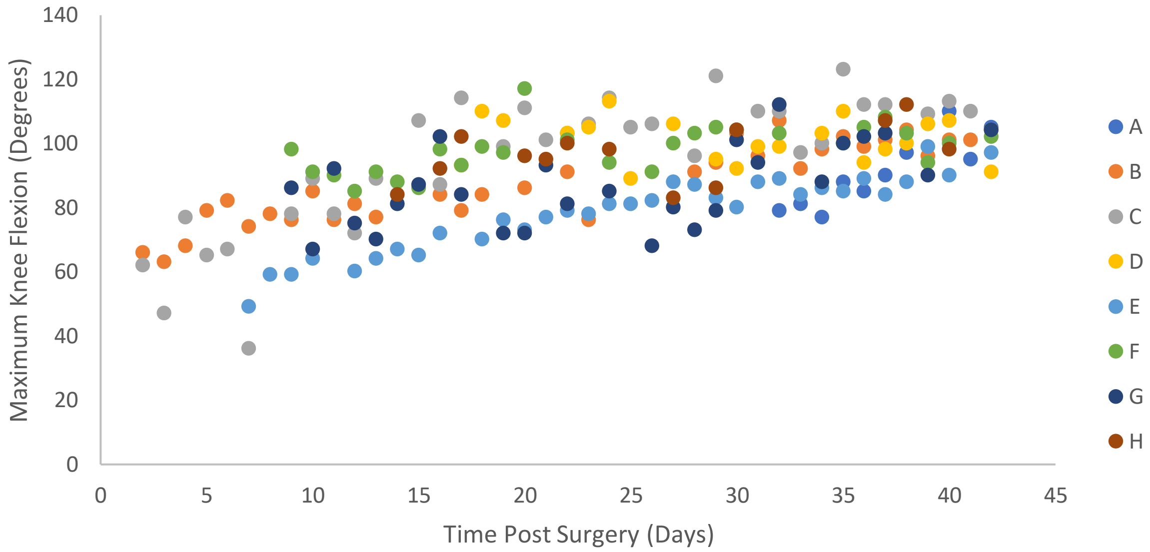


Figure 11: Raw daily maximum knee flexion for each participant

f)

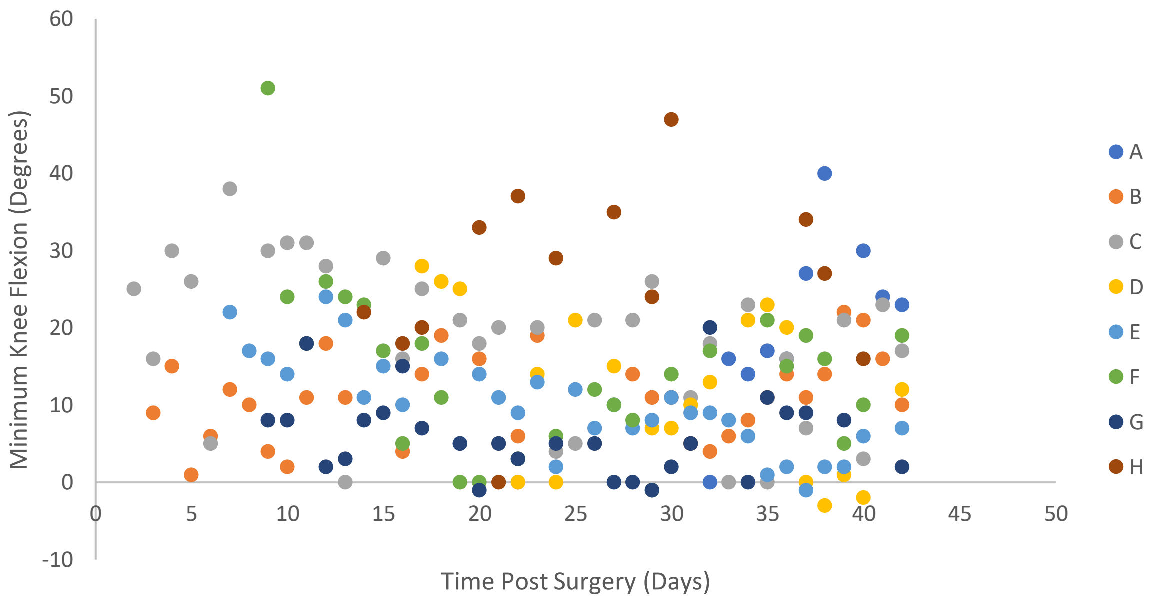


Figure 12: Raw daily minimum knee extension for each participant

g)

Table 8: Compliance to performing heel slide activity across intervention period

Participant	Compliance (%)
A	83
B	80
C	88
D	78
E	92
F	79
G	82
H	48

h)

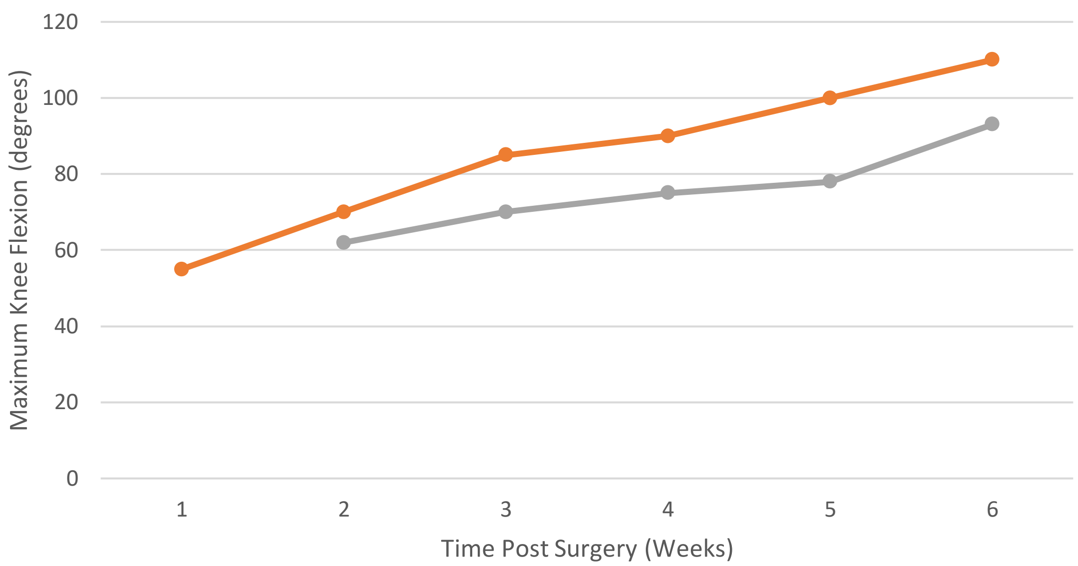


Figure 13: Observational experiment comparing weekly knee flexion progress between a goniometer measurement and Digital Knee measurement. Orange circles represent goniometer measurements, Grey circles represent Digital Knee measurements.

i)

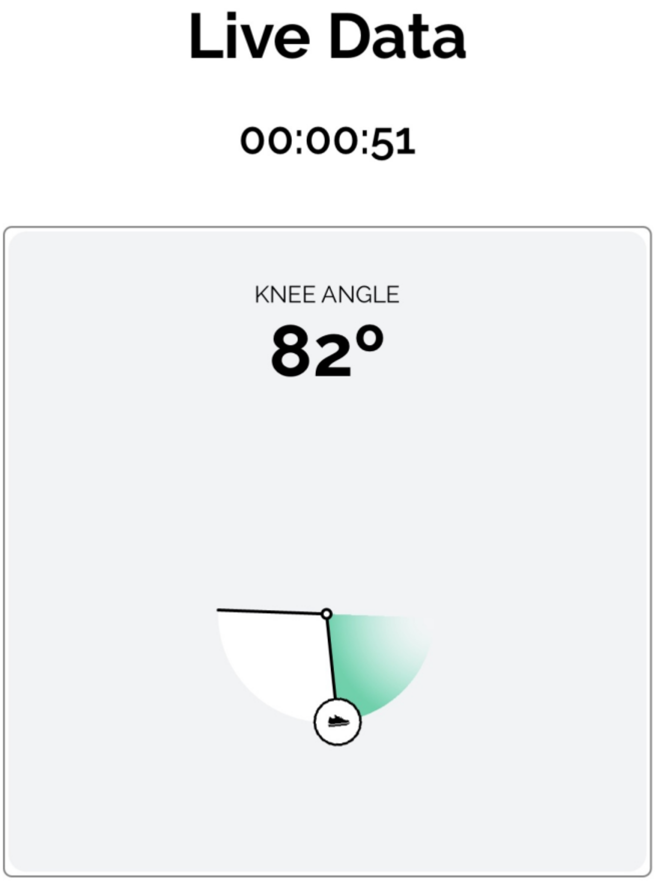


Figure 14: Updated live data display in the OPUM active

Appendix C

GRADUATE RESEARCH SCHOOL

AUT

FORM PGR16 APPLICATION FOR EMBARGO

PLEASE NOTE

- ***This form must be typed. Handwritten forms will not be accepted.***
- ***Double clicking on the check boxes enables you to change them from not-checked to checked.***
- ***The completed form, signed by the student and the primary supervisor, should be submitted to the appropriate Faculty Postgraduate Office when the thesis/exegesis is lodged for examination. If the application is approved by the Faculty Postgraduate Committee, the form will be signed by the Dean and sent to the Graduate Research School for insertion into the print copies deposited. For more information consult the Postgraduate Handbook.***

Student ID	17981118	**Name**	Anja van Gulden
Faculty	**Health & Environmental Sciences**	**School/Dept**	Sport and Recreation
Programme	**Master of Sport and Exercise**	**Date of submission for examination**	23/05/2022
Research Output	**Thesis** ☒ **Dissertation** ☐	**Exegesis** ☐	**Points Value** 120
Research Title	The influence of a smart wearable device on early stage ACLR rehabilitation		

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Mentor of Primary Supervisor	Chris Whatman	**Signature**		**Date**	19/01/21

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