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Assessing the Validity of a Kinematic Knee Sleeve in a Resistance-Trained Population †

Nathan Toon [1,*], Simon McMaster [2], Tom Outram [1] and Mark Faghy [1]

1 Human Sciences Research Centre, College of Science and Engineering, University of Derby, Derby DE22 1GB, UK; t.outram@derby.ac.uk (T.O.); m.faghy@derby.ac.uk (M.F.)
2 Footfalls and Heartbeats (UK) Limited, Nottingham NG7 1FW, UK; simon@footfallsandheartbeats.com
* Correspondence: n.toon@derby.ac.uk
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Abstract: The current study assessed the validity of a Kinematic Knee Sleeve (KiTT) against a gold-standard motion-capture system (Vicon, Oxofrd, UK). The relative knee angle, measured in the sagittal plane (RKA), was measured across a range of sporting movements to allow for comparisons and agreement between systems. The results demonstrate a high degree of validity of KiTT during a squat, deadlift, and leg curl, with partial validity of a leg extension (0.98, 0.97, 1.01, 1.31, respectively). KiTT serves as a valid method to collect information on the RKA. The KiTT appears to serve as a practical alternative to Vicon without sacrificing the quality of the data.

Keywords: kinematic; validity; knee; textiles; wearable; sensor; three-dimensional

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1. Introduction

Three-dimensional (3D) motion-capture systems are acknowledged as the gold-standard technological method to investigate movement patterns and biomechanics [1]. Motion-caputre sysyems are capable of recording joint angles such as the relative knee angle in the sagittal plane (RKA), the displacement of segments, and the angular motion of joints/segments [2,3]. RKA is commonly measured when assessing squat depth to provide the user/coaches with information relating to range of motion or strength improvements that can be used to develop effective strength and condtioning strategies and rehabilitation plans [1–4]. However, when recording motion through such systems, real-time data are not available, comprimising the data's value during a particular session. Additionally, these systems are not as accessbile and are coupled with the need for specialist equipment and training. Specialist moition-capture systems are also fixed within a specific location, affecting ecological validity.

Wearable sensors that can be worn away from specilist settings and provide real-time and instantaneous data to users and coaches are an attractive propostion [5]. Being able to access real-time data allows exercise or training methods to be adjusted instantly, suiting the needs of the session to aid performance/rehabilitative progress in a way that is not possible with fixed and speicalist motion-capture systems [5,6]. Previous wearable sensors, such as smart watches, have focused on comfort for the user, rather than the quality of data. As a result, accuracy in the data is often lost, leading to unrelaible and invalid data, limiting its use and applicability within applied practice [7,8].

An innovative technology developed by Footfalls and Heartbeats (UK) Limited (Nottingham; FHL) aims to bridge the gap between comfort and the production of valid data sets. The Kinematic Knee Sleeve (KiTT) is a custom-knitted smart wearable knee sleeve, which is the first of its kind that knits the sensor directly into the fabric. Part of the KiTT is an electronics module, allowing data from the textile strain sensor to be transmitted to a portable device; however, validation against criterion methods has yet to be conducted.

Accordingly, the aim of the current study was to investigate the validity of the KiTT against the gold-standard motion-analysis system.

2. Materials and Methods

2.1. KiTT Structure

KiTT (Version 7.3) was knitted as a single piece of textile using a Stoll CMS ADF 32 W knitting machine (Karl Mayer Stoll, Reutlingen, Germany). The main body of KiTT consists of lycra (22 dtex) and polyamide 6.6 (78/24/1 dtex, Zimmerman, Weiler-Simmerberg, Germany). This combination of yarn was plated with nylon (78/1 dtex, Progressive Threads Ltd., Nottingham, UK). The cuff only consists of lycra (78/20/1 dtex, Stretchline, Nottingham, UK).

The textile strain sensor was measured 85mm $\times$ 7mm (height $\times$ width), consisting of silver-plated nylon yarn (Statex Shieldex®, 117/17 dtex; electrical resistivity <1.5 KΩ/m, Bremen, Germany), which was knitted alongside regular nylon yarn (78/1 dtex, Progressive Threads Ltd., Nottingham, UK). The transmission lines consisted of silver-plated nylon yarn (Statex Shieldex®, 235/36 dtex; electrical resistivity <80 KΩ/m, Bremen. Germany).

2.2. Participants

Following informed consent, 10 participants (8 male) were recruited for the current study, with an average age of 30.1 $\pm$ 11.7 years, weight of 78.5 $\pm$ 15.7 kg, and height of 177.7 $\pm$ 8.4 cm. Ethics approval was provided by the University of Derby Human Science Research Ethics Committee (ETH2021-0579). The inclusion criteria ensured that participants had >2 years experience of resistance training; completed ~150 min/week of moderate-intensity exercise; and completed the University health screen questionnaire.

2.3. Procedure and Protocol

Two data-collection systems were used for the current study; KiTT (version 7.3, *FHL*) and a Vicon motion-capture system (Oxford, UK). KiTT requires a small electronic unit to be connected to press-studs within the knee sleeve. This allows data to be transferred concurrently to a base station connected to a Windows 10 PC during the sporting movement. KiTT was worn on the left knee with the electronics lateral to the knee. Vicon has been used extensively in the assessment of human movement research [1]. Vicon utilises a Vicon Vantage Capture System, along with two Vicon 720p Colour Bonita Cameras. A total of 16 retro-reflective markers were attached to the participant following the Plug-In GAIT Lower-Body AI model created by the Vicon Nexus system.

The current study used four sporting exercises. Back squat (SQ) and traditional deadlift (DL) were weighted with a self-selected weight (33.5 $\pm$ 12.3kg) and was not sufficient enough to induce fatigue throughout the study. The remaining exercises, a leg curl (LC) and a leg extension (LE), were modified due to machine availability. A resistance band, ankle cuff, and dumbbell were configured to allow for either knee flexion (LC) or extension (LE).

Participants attended the Human Performance Unit at the University of Derby on three occasions. The first session included a full familiarisation, and sessions two and three comprised of experimental data collection. Data-collection sessions used only one motion-capture system, which was randomised for each participant's visit. Participants completed all exercises in a set order, with each exercise consisting of five repetitions followed by 2 min rest. The final visit was identical in design but involved a second motion-capture system.

2.4. Data Analysis

RKA was only recorded from the left limb due to KiTT only being able to record left-limb motion data. From Vicon's data output, only left-limb RKA was taken for the current study. KiTT's raw data were converted into relative knee angle through hysteresis analysis and reference points for the whole movement [9]. Vicon quantifies RKA through the automatic tracking of retro-reflecive markers and embedded formulas and equations [1].

Mean and standard deviations were calculated, enabling comparisons between the two motion-capture systems. Bland and Altman (B&A) plots were used to assess the degree of validity of KiTT when compared to criterion methods. A 95% confidence interval was used to identify agreement within the two systems [10]. A peak angle, defiend as the point of greatest knee flexion (SQ, DL, and LC) or greatest knee extension (LE), was when RKA was recorded.

3. Results

Raw data display high validity between the two motion-capture systems (Table 1). Small–moderate differences (2–26%) were displayed in the KiTT compared to Vicon across each exercise (2.69° SQ, 1.51° DL, 1.48° LC, and 2.85° LE). There was high validity across three of the four exercises in the KiTT compared to Vicon, which can be observed in Figure 1.

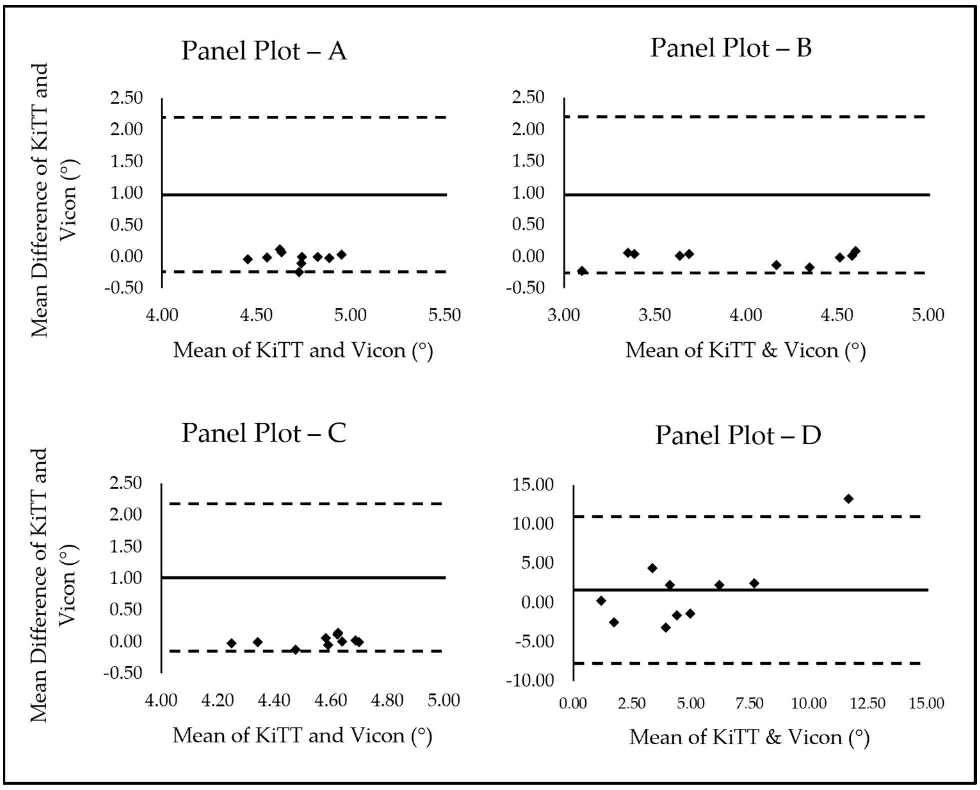

Figure 1. Panel plot of four Bland and Altman Plots: (**A**) B&A plot of the squat; (**B**) B&A plot of the deadlift; (**C**) B&A plot of the leg curl; (**D**) B&A plot of the leg extension.

Table 1. Relative knee angle from each sporting exercise (n = 10).

	Relative Knee Angle (°)			
Collection System	**Squat**	**Deadlift**	**Leg Curl**	**Leg Extension**
KiTT	111.33 ± 17.62	58.16 ± 31.06	96.44 ± 15.08	6.72 ± 6.02
Vicon	114.02 ± 18.02	59.67 ± 30.76	94.96 ± 12.52	3.87 ± 2.15
Similarity (%)	98	97	98	74

Before creating B&A plots, a test for heteroscedasticity was conducted. A positive result was found with SQ, DL, and LC, but not LE. As a result of this, SQ, DL, and LC raw data were translated into natural logarithmic data for the panel plots. Panel plots A, B, and C display the data points within the 95% Limits of Agreement, establishing validity in the KiTT. Panel plot D displays 90% of the data fitting within the 95% Limits of Agreement, establishing only partial validity with the KiTT for this specific exercise.

4. Discussion

The KiTT is a wearable technology that demonstrates a high level of validity against criterion laboratory assessment methods when completing whole body-exercise used in strength and rehabilitation environments. This is important as the KiTT could capture data in a non-controlled and specialist environment that is accessible by wider user groups. Motion-capture systems require markers to be affixed to the user, along with the calibration of the camera system and time-consuming data processing [1]. The KiTT only requires the sleeve to be worn on the user, with a Bluetooth connection established to the base station. For users and coaches, this can be invaluable, as data-collection time is significantly reduced, with data being generated instantaneously. Unlike motion-capture systems, the KiTT is not bound to a performance area where movement may be restricted; leading to increased ecological validity.

Low-similarity measures of RKA during the LE can be explained by the timing of measurements. The peak knee angle during the LE occurs when the textile is under rebound, where there is no tension throughout the sensor. As a result of this, it was not possible to obtain an accurate reading of RKA for this specific exercise, unlike SQ, DL, and LC. Through research and development, this issue may be resolved, leading to consistently valid data throughout collection.

Fixed motion-capture systems require direct line-of-sight to the markers, which can make the system inaccessible for specific exercises, such as squats and leg curls. On the other hand, the KiTT provides a unique method of assessment that is not bound to a specific performance area. Therefore, future research into the KiTT's validity and practicality should consider more dynamic and explosive movements. As the scope of this study was only inclusive of movements performed in a controlled environment, there is little/no evidence that the KiTT is a valid measurement tool in a more practical environment, thus warranting more extensive investigation into its practical uses and ecological validity.

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Institutional Review Board Statement: This study was conducted according to the guidelines of the Declaration of Helsinki and approved by the supervisors of the current study and the Ethics Committee of the University of Derby (Project Code: ETH2021-0579 on 5 March 2021).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ethical obligations.

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