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Validity of wearable sensors for total knee arthroplasty (TKA) rehabilitation: A study in younger and older healthy participants

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ABSTRACT

Background: With 100,000 total knee arthroplasty (TKA) procedures taking place in the United Kingdom annually, the demand on rehabilitation services is high. Most regimes are home-based. Without clinician-patient interaction, detection of rehabilitation concerns can be delayed, reducing the chance of successful early intervention. Wearable technologies, such as MotionSense™ (Stryker, US), may offer a solution to this problem by remotely supporting post-operative TKA rehabilitation through the provision of personalised rehabilitation and tracking of home exercises, enabling healthcare professionals to continuously monitor rehabilitation progress remotely. Validation of such devices against a known kinematic model in activities of daily living is important for confident interpretation of resulting clinical data. The aim of this study therefore was to validate the accuracy of MotionSense™ against a clinical motion capture standard.

Methods: Twenty younger and 14 older healthy, able-bodied adults attended one testing session (Younger: 24 ± 4 years old; Older: 71 ± 5 years old). Movement was tracked using Vicon motion analysis and a Plug-In-Gait lower body model was applied to all participants. Three activities were performed – walking, stair ascent, stair descent. The knee flexion angle root mean square error (RMSE) between the technologies was determined.

Results: For both groups the knee flexion RMSE remained below 3° for all activities. The combined RMSE for all adults was 2.4° for walking, 2.7° for stair ascent, and 2.6° for stair descent. The signed error increased during the swing phase of gait.

Conclusion: MotionSense™ was found to accurately estimate knee flexion angles during several common activities compared to Vicon motion capture.

1. Introduction

Total Knee Arthroplasty (TKA) is an effective operation for alleviating pain, restoring knee functionality, improving quality of life, and decreasing morbidity for those with knee osteoarthritis [1]. The number of TKA procedures is increasing each

Abbreviations: TKA, Total Knee Arthroplasty; RMSE, Root Mean Square Error; IMU, Inertial Measurement Unit.

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year, with currently over 100,000 performed annually in the UK [2] and over 700,000 in the US [3], with future surgical volumes predicted to continue this trend and further increase substantially [4]. However, it is widely reported that up to 15–27% of patients experience ongoing pain or reduced physical function postoperatively and may be dissatisfied with their TKA [5,6]. Whilst ongoing symptoms can greatly burden the individual, societal impact includes increased health care costs, including additional follow-up, investigations, rehabilitation and the huge expense associated with revision procedures as well as socio-economic factors such as difficulties returning back to work and reduced independence [1].

Rehabilitation can improve functional outcomes, leading to successful post-operative outcomes [7]. Although improvements in knee function can continue for up to one year [8,9], and beyond in specific populations [10], a large proportion of range of motion (ROM) gains for both flexion and extension occur in the early post-operative period, which can be as early as 4 weeks after TKA [11]. Most regimes are now home-based and rely on patient compliance. Previous research has reported that adherence to rehabilitation is poor, leading to unsuccessful rehabilitative outcomes and approaches being altered unnecessarily [12]. Moreover, without evidence of functional progress, patients can lack motivation which affects adherence to rehabilitation, again resulting in suboptimal outcomes [12]. Although home-based rehabilitation has reported superior patient satisfaction [13,14], many reports state difficulties in managing home-based rehabilitation due to lack of guidance, limited clinician-patient interaction, and minimal follow-up appointments following discharge [15]. The ability to accurately quantify knee function in the home is therefore important to improve adherence, and to provide early warning if there is evidence that intervention with a healthcare professional if necessary.

Wearable technologies that can accurately measure knee flexion may offer a frequent quantitative assessment of knee function with greater resolution than subjective survey-based outcome measures [16]. This is facilitated by their ease of use and application without professional assistance enabling patients to continuously monitor from their own home. Furthermore, when paired with an App they may provide instructional information and real-time feedback. Stryker have developed a wearable device called MotionSense™ which remotely supports post-operative TKA rehabilitation, providing personalised regimes, tracking of home exercises, and enabling healthcare professionals to continuously monitor rehabilitative progress remotely. The wearable device utilises two inertial measurement units (IMUs), above and below the knee, with knee angle provided using a Madgwick filter [17].

For clinical interpretation, it is important for wearable sensors to provide accurate and reliable information. There is limited literature on the validity of wearable sensors to assess knee function, particularly during functional activities, such as walking and stair climbing, and especially in a relatively large control group that presents an opportunity to age-match to a TKA population [18–20]. Typically, investigations have recruited younger cohorts with maximum 3–12 individuals, all assessing different IMU technology and algorithms against different 3D motion capture systems and models [18–20]. Three-dimensional motion capture systems are the gold standard for movement analysis producing accurate and precise results. Multiple cameras track retroreflective markers attached to patients who wear tight-fitting clothing and perform movement within the camera's capture volume. The equipment, time, and expertise required to perform an assessment using the 3D motion capture has limited its use in clinical practice, however the 3D motion capture can validate the IMUs which address each of these limitations.

The aim of the study was to determine the accuracy of knee angle data captured by the MotionSense™ IMU compared to a clinical 3D motion capture standard on healthy younger and older individuals.

2. Method

2.1. Study Design

This was a single cohort study and received NHS R&D approval (IRAS project ID 314702).

2.2. Participants

Invited subjects were all healthy, able-bodied adults (Table 1) who met the necessary inclusion criteria of being free from any known lower limb musculoskeletal injuries or previous surgeries, and able to perform specific activities of daily living. Participants were categorised into one of two groups dependant on age. Two groups of adult participants were recruited from two different populations, accessed through the Department of Biomedical Engineering at the University of Strathclyde, and through the University of Strathclyde's Aging Network. No upper age criterion was applied for each population, but we expected the two samples to naturally differentiate into younger and older age groups. All participants provided written consent before participating.

2.3. Instrumentation and protocol

Each participant attended one testing session either at the biomechanics laboratory at the University of Strathclyde or the Human Performance Laboratory in the Clinical Research Facility of the Glasgow Royal Infirmary. The Plug-In-Gait lower body model marker set (Vicon Motion Systems, Oxford, UK) was applied to each participant (Figure 1a), as well as two MotionSense™ sensors placed on the lateral thigh and lower leg on one side only (Figure 1b). For the younger adults the

Table 1
Descriptive statistics for participants. Results are presented as mean (SD) for continuous data and number for dichotomous data.

	Younger adults	Older adults	All Participants
Number of participants	20	14	34
Age (years)*	24.1 (3.85)	70.6 (5.42)	43.2 (23.67)
Age Range (years)	20–36	60–84	20–84
Weight (kg)	69.1 (12.96)	72.4 (12.60)	70.4 (12.73)
Height (m)†	1.8 (0.11)	1.7 (0.09)	1.7 (0.11)
Body Mass Index (kg/m^2) †	22.3 (2.87)	25.5 (3.22)	23.6 (3.37)
Sex (F/M)	8 / 12	10 / 4	18 / 16
Physical activity level (H/M/L)	11 / 9 / 0	12 / 2 / 0	23 / 11 / 0
Dominant Limb (R/L)	18 / 2	12 / 2	30 / 4
Lower Limb sensor worn (R/L)	10 / 10	14 / 0	24 / 10

F: Female; M: Male; R: Right; L: Left; H: High; M: Medium; L: Low.
* $p < 0.001$ between younger vs older adults.
† $p < 0.05$ between younger vs older adults.

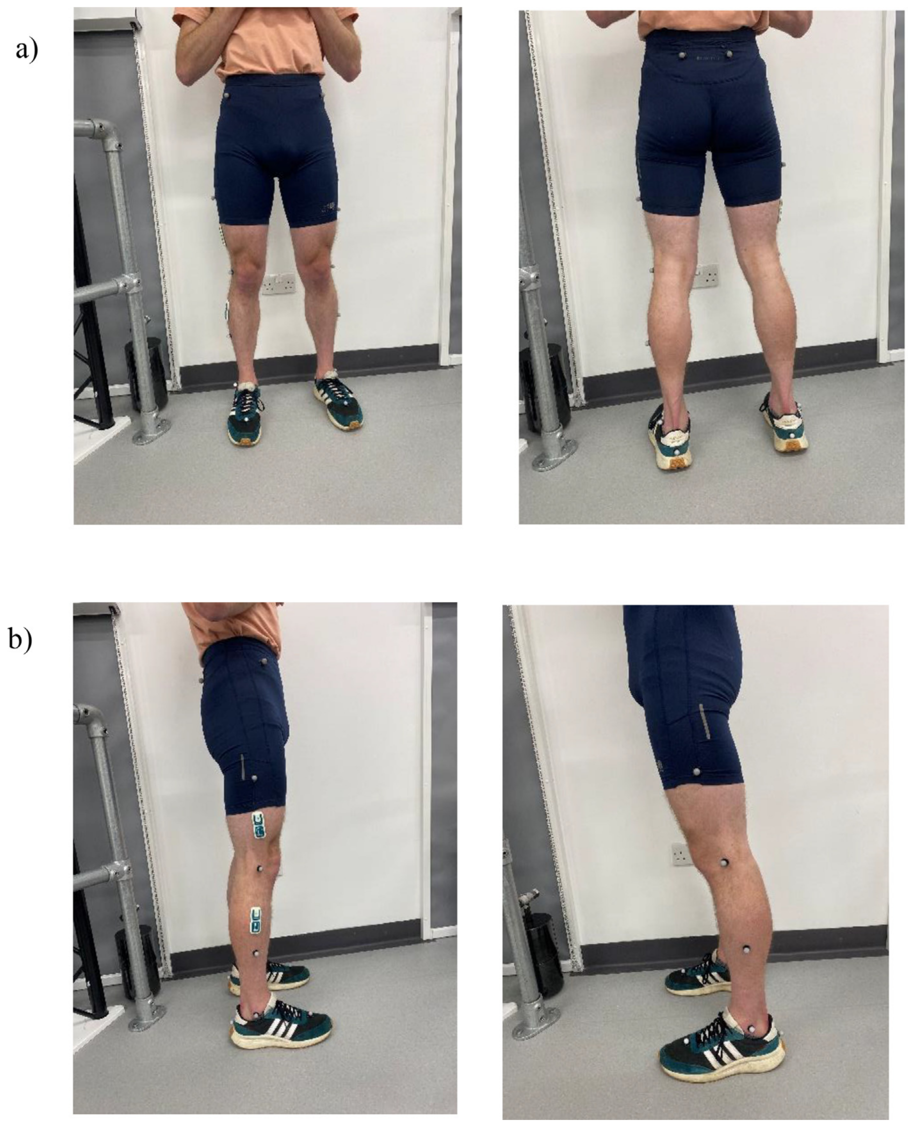

Figure 1. A) participant with lower body plug-in-gait marker model, and b) left and right sagittal view of participant with MotionSense™ sensors attached.

MotionSense™ sensor was randomly worn on the left or right side, however for the older adults this was only worn on the right side. Older adult data was collected in the Clinical Research Facility which required the sensor to be worn on the right side to facilitate video capture. The markers were tracked by a 12-camera Vicon T-series system at the University of Strathclyde and a 15-camera Vicon Bonita system at the Glasgow Royal Infirmary (Vicon Motion Systems, Oxford, UK). The MotionSense™ sensors each consisted of a triaxial IMU, including a gyroscope, accelerometer, and magnetometer. The data was received and collected via Bluetooth to an App on a mobile device in real-time, and converted to knee angle. A Madgwick filter first estimated orientation and then the transform between the two sensors reported knee angle.[17].

Participants completed three activities: 1) treadmill walking, 2) stair ascent, and 3) stair descent (Figure 2). For the treadmill walking, participants had a one-minute habituation period to select a comfortable walking speed that was then fixed for five minutes. Both the stair ascent and descent were completed three times per trial, with three trial repetitions, totalling nine ascents/descents of the stairs.

2.4. Data analysis

Data were post-processed in Vicon Nexus to output knee joint kinematics using standard Plug-In-Gait algorithms. The MotionSense™ sensor data was exported in real-time to an App on which a proprietary algorithm determined knee flexion. The 3D motion analysis and MotionSense™ sensors were compared in the sagittal plane only given that MotionSense™ only measures knee flexion and extension.

To compare the two technologies a semi-automated process was created in Matlab (MATLAB R2023a, The MathWorks Inc., USA). Vicon and MotionSense™ data were filtered applying a fourth order zero lag Butterworth filter with a cut off frequency of 8 Hz. The sampling frequency differed between Vicon (100 Hz) and MotionSense™ (~50 Hz). Therefore, MotionSense™ data was upsampled to 100 Hz, to match the sampling frequency of the Vicon data. The two signals were time-synchronised over the activity period by maximising the cross-correlation of the signals.

Manual application of the reflective markers and sensors on the leg can result in a different zero angle for the knee for each technology. This offset difference was removed by adjusting the MotionSense™ data so that its mean value equalled that of Vicon across the entire activity. This difference was typically small and resulted in a more meaningful comparison of the technologies by minimising any manual experimental errors resulting from marker and sensor placement.

Heel strike was manually determined from a bespoke graphical user interface to identify 10 gait cycles for analysis during the walking activity, and one step for both the stair ascent and stair descent. Despite participants performing a 4-step ascent and descent only one full gait cycle per trial could be analysed from heel strike to heel strike. Series were time-synchronised again in each gait cycle to account for minor variation on the time signature of the MotionSense™ device.

2.5. Statistical analysis

The accuracy of the MotionSense™ data was evaluated using the mean signed error and root mean square error (RMSE) between the Vicon and MotionSense™ series in the gait cycle, and across the entire activity. A clinically significant difference between measures was taken if the difference exceeded ± 5°, and RMSE values < 3° were considered acceptable, which is similar to documented knee angle accuracy measurements [21–23]. Maximum and minimum knee angles in addition to

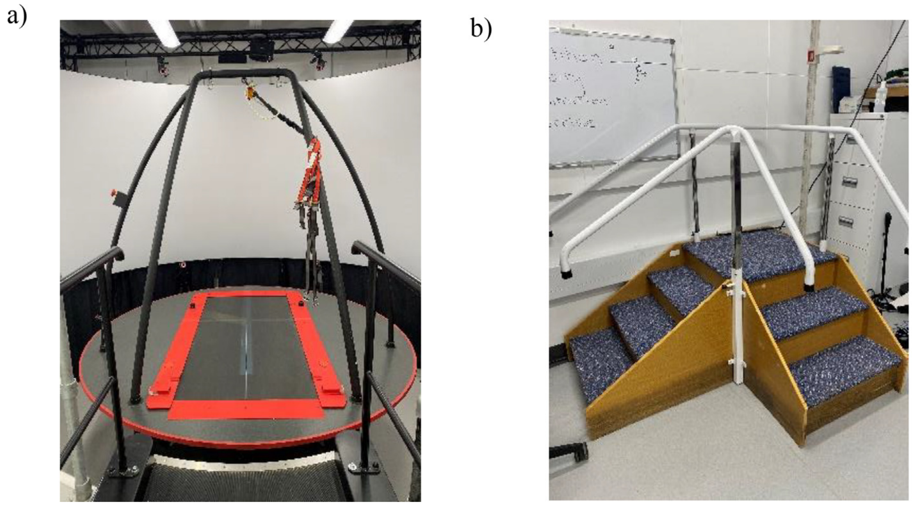

Figure 2. Laboratory set up for a) treadmill walking, and b) stair ascent/descent for one laboratory (second laboratory stairs not shown).

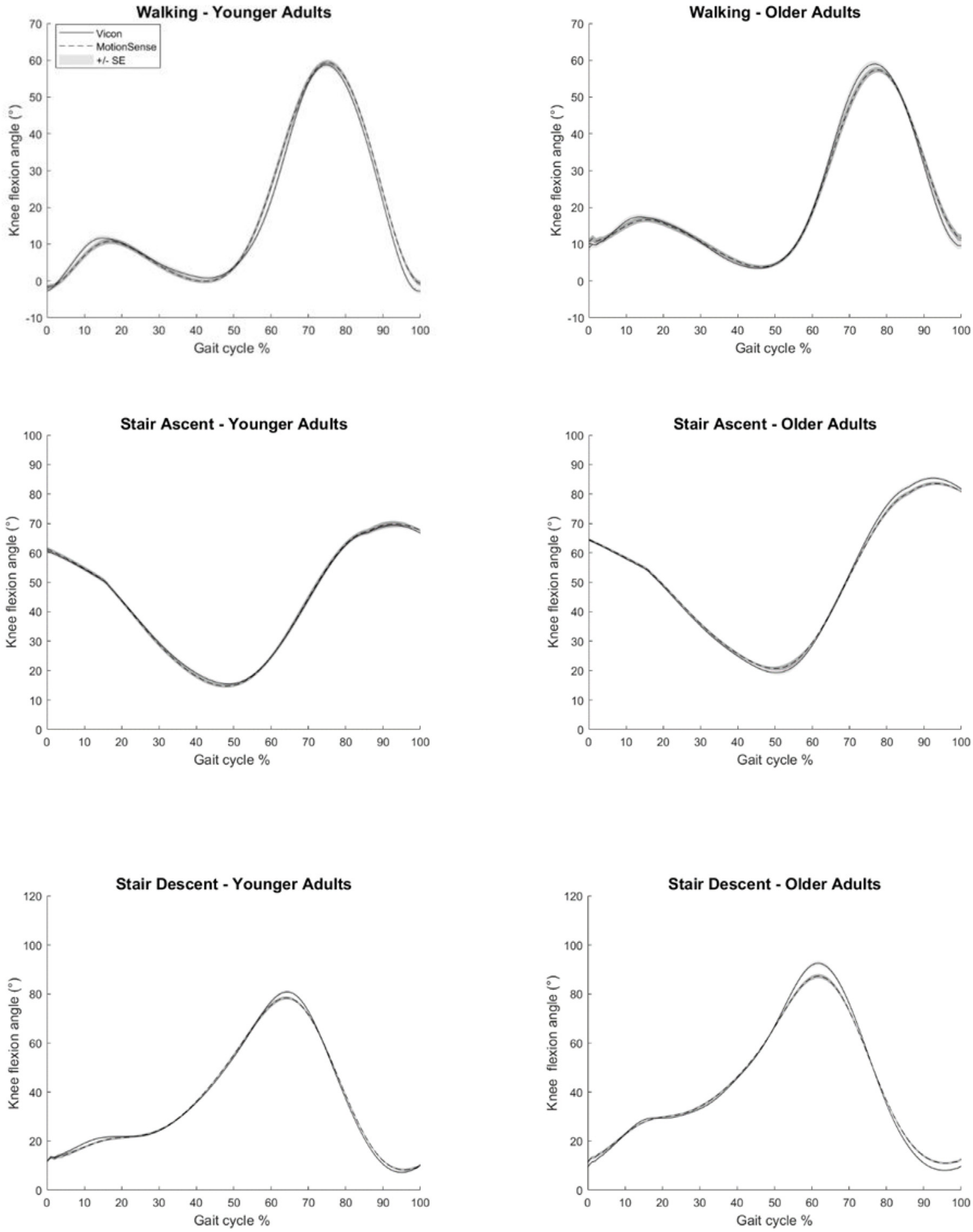

Figure 3. Mean knee flexion (and standard error) from 10 gait cycles to compare the Vicon 3D motion capture system and the MotionSense IMU. Each gait cycle starts from initial contact and includes the stance and swing phase of the gait cycle. The closer the lines are to each other signifies greater agreement between the two measurement devices.

the range of motion, for both the processed Vicon and MotionSense^{TM} data were determined from each gait cycle, and averaged across all gait cycles (mean ± SD).

One-way ANOVA compared participant demographics and all outcome measures. One participant was removed from the stair ascent and descent analysis due to missing data which prevented the gait cycle analysis (n = 19 young healthy adults). A

Table 2
Mean knee angle (SD) results for all activities for younger and older adults.

		Knee Angle (°)								
		Max Flexion			Min Flexion			ROM		
		Vicon	MS	Δ	Vicon	MS	Δ	Vicon	MS	Δ
Younger adults	Walking	59.4 (6.1)	59.8 (5.5)	0.6 (8.2)	−3.5 (4.0)	−2.8 (4.5)	−0.7 (6.1)	62.8 (4.7)	62.6 (4.4)	0.3 (6.5)
	Stair Ascent	87.1(12.7)	85.8 (11.9)	1.3 (3.6)	6.5 (5.9)	6.7 (6.6)	−0.3 (2.1)	80.3 (13.5)	78.7 (11.9)	1.7 (4.9)
	Stair Descent	85.7 (10.8)	82.1 (9.5)	3.6 (2.5)	6.0 (5.5)	6.6 (5.9)	−0.6 (1.9)	79.7 (11.2)	75.5 (9.0)	4.2 (4.1)
Older adults	Walking	59.9 (8.4)	58.8 (7.9)	1.0 (2.9)	2.5 (6.2)	2.1 (7.2)	0.4 (2.3)	57.4 (6.1)	56.7 (5.5)	0.7 (4.3)
	Stair Ascent[a]	97.2 (7.1)	93.4 (8.3)	3.8 (2.2)	10.6 (5.7)	14.0 (6.8)	−3.4 (2.9)	86.6 (4.8)	79.4 (5.6)	7.2 (3.8)
	Stair Descent[a]	97.5 (6.5)	91.5 (7.7)	5.8 (3.1)	6.1 (4.8)	9.7 (6.1)	−2.9 (2.1)	91.0 (4.7)	82.4 (5.8)	8.6 (4.1)
All adults	Walking	59.6 (7.0)	59.4 (6.7)	0.2 (3.1)	−1.0 (5.8)	−0.7 (6.2)	−0.3 (2.4)	60.6 (5.9)	60.1 (5.6)	0.4 (3.6)
	Stair Ascent[c]	91.0 (11.9)	88.3 (11.3)	2.7 (3.4)	8.0 (5.9)	9.7 (7.6)	−1.7 (2.7)	83.0 (11.1)	78.6 (9.9)	4.4 (5.3)
	Stair Descent[b,c]	90.7 (10.9)	86.1 (9.9)	4.6 (5.4)	6.3 (5.2)	7.8 (6.1)	−1.6 (2.4)	84.4 (10.5)	78.3 (8.4)	6.1 (4.8)

Max: maximum; ROM: range of motion; MS: MotionSense™; Δ: difference between Vicon and MotionSense™ (and pooled SD).
[a] $p < 0.05$ between Vicon and MS for range of motion in older adults.
[b] $p < 0.05$ between Vicon and MS for maximum flexion for all adults.
[c] $p < 0.05$ between Vicon and MS for range of motion for all adults.

Table 3
Mean RMSE (SD) results for all activities for younger and older adults.

	Younger Adults	Older Adults	All Adults
	RMSE (°)		
Walking	2.41 (0.85)	2.39 (0.68)	2.40 (0.77)
Stair Ascent	2.77 (0.83)	2.60 (0.96)	2.70 (0.88)
Stair Descent	2.41 (0.77)	2.83 (0.99)	2.59 (0.88)

RMSE: Root Mean Square Error.

pooled analysis of the younger and older populations was also conducted for each activity. All statistical analysis was performed using SPSS Statistics (SPSS Statistics v. 26, USA) using a 0.05 level of significance.

3. Results

In addition to age, height and weight also differed between the younger and older adults (Table 1, $p < 0.05$) and the older group walked significantly slower than the younger group (0.94 ± 0.12 ms^{-1} vs 1.17 ± 0.07 ms^{-1}, mean ± SD, $p < 0.001$, respectively).

However, knee flexion patterns for the younger and older adults were similar for all activities measured (Figure 3). The greatest variation within the groups, as shown by the grey shading of the standard error, occurred during the swing phase for both groups and activities. The maximum and minimum flexion angles over the 10 gait cycles are detailed in Table 2. For all variables MotionSense™ recorded a smaller range of motion, reaching lower values of both flexion and extension. The difference between Vicon and MotionSense™ was greater in flexion than extension, recording a maximum difference of 5.82° between maximum flexion for older adults during stair descent ($p < 0.05$) and of −3.41° between minimum flexion for older adults also during stair descent ($p > 0.05$).

The RMSE for all activities and age groups ranged between 2.39° to 2.83° (Table 3). For younger and older adults, walking demonstrated the highest agreement, while the stair ascent activity demonstrated the lowest agreement. The RMSE was smaller for older adults across all activities, with a maximum discrepancy of 0.42° between younger and older adults which was reported during stair descent. There were no significant differences between RMSE for the younger and older participants. Pooling the groups led to walking having the smallest RMSE and stair ascent the highest RMSE.

Figure 4 depicts a Bland-Altman-like plot to assess whether the signed difference between the technologies varied with the mean knee flexion. Differences only became unacceptable at high flexion in the older stair descent activity, as the knee flexion approached 90°. Figure 5 describes the same signed difference as a function of the gait cycle percentage. Walking reported the smallest differences across the gait cycle with a maximum error around toe-off (−3.93° difference) and just before heel strike (−3.12° difference) of the gait cycle for younger and older adults, respectively. For the Stair Descent the error peaked around toe off in the younger (+2.66° difference) and older (+5.68° difference) adults, respectively. For the Stair Ascent the error peaked at in the swing phase nearing heel strike for older adults (+4.16° difference), and at 100% of the gait cycle for younger adults (−3.22° difference). For all these activities the maximum error coincides with peak flexion for both the older and younger populations.

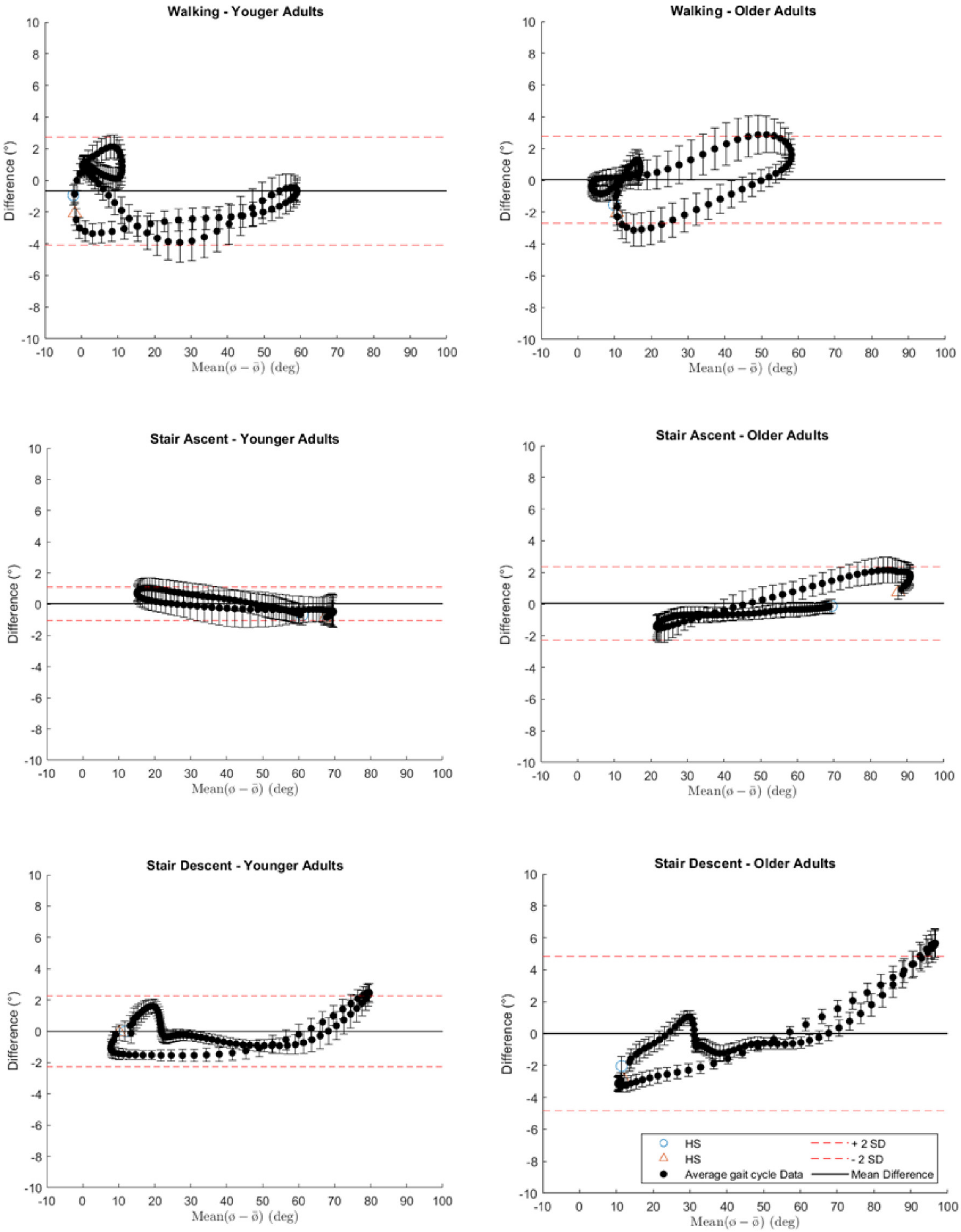

Figure 4. Bland-Altman- like plots of the mean error between the measurement technologies over whole gait cycle. Error bars display one standard error. A negative difference reports an underestimation of knee angle by MotionSense™, and a positive difference an overestimation.

4. Discussion

The greatest change in ROM for both flexion and extension has been shown to occur in the first 4 weeks post-TKA [11], with greater ROM and walking ability associated with greater patient satisfaction [24]. Wearable technologies can remotely

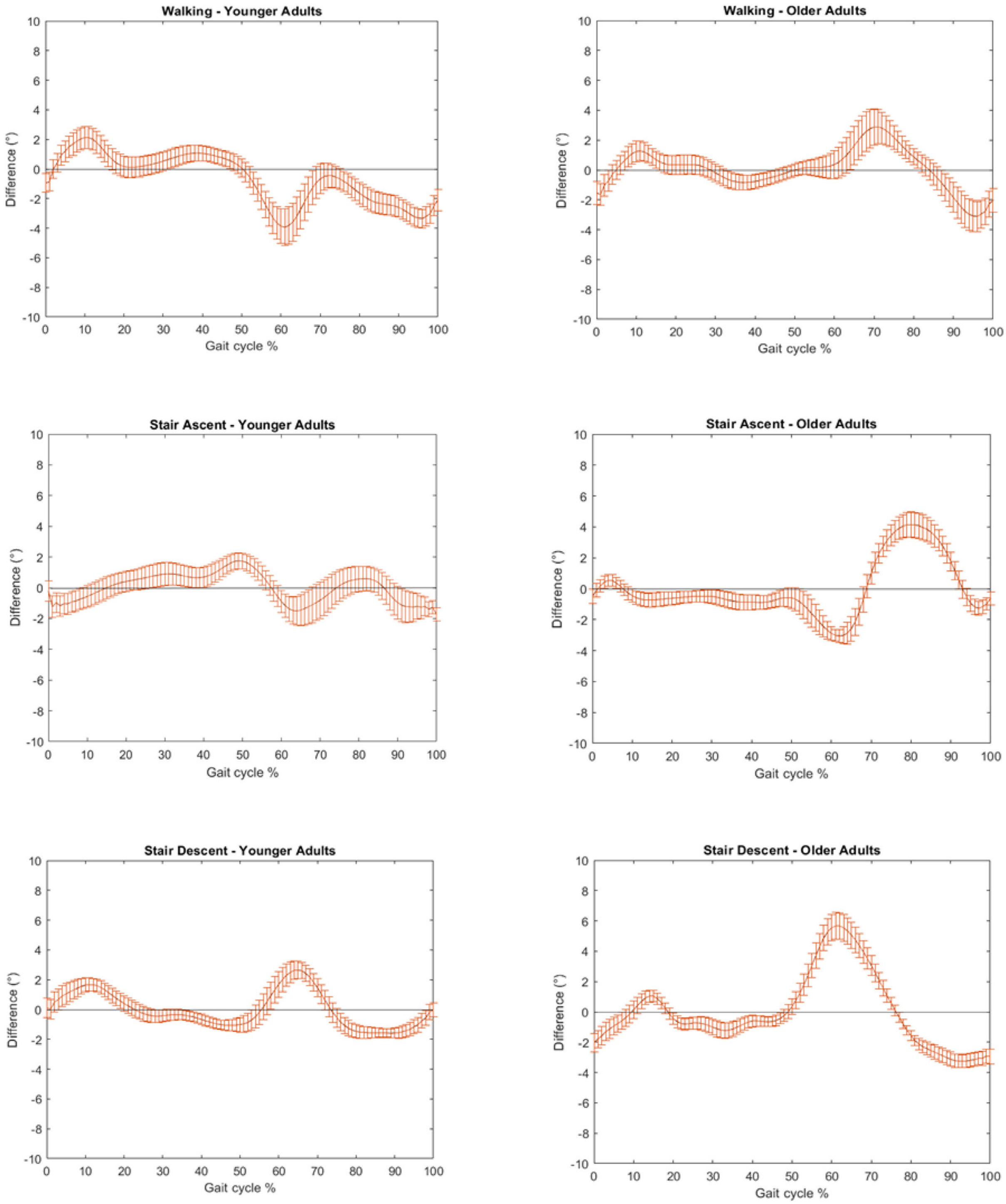

Figure 5. Signed error between the measurement technologies over whole gait cycle. Error bars display one standard error. A negative difference reports an underestimation of knee angle by MotionSense^{TM}, and a positive difference an overestimation.

and continuously monitor and assess patient progress, which may enhance home-based rehabilitation, particularly over this initial phase of rehabilitation. However, it is important that these track movement accurately. In this study the MotionSense^{TM} sensors performed accurately during all activities compared to a gold standard motion capture system on healthy individuals of all ages and abilities.

The majority of measured activities revealed an acceptable agreement of < 3°. This represented a closer agreement than other similar gait studies, all reporting results within a larger threshold of < 5° [18,19]. Most recently in healthy populations, McGrath et al. [18], Berner et al. [22], and Rekant et al. [23] conducted validation analyses between motion capture and IMU sensors reporting knee flexion RMSE values of 3.3–3.77° and excellent coefficients of multiple correlation values of 0.84–0.99, respectively. Of the previous research all was conducted in small young healthy adult populations over 6–15 gait cycles [18,19]. Over 10 gait cycles, our results did not exceed an RMSE of 2.41° in a much larger sample population of both older and younger healthy adults. Despite the different age groups, and significantly slower gait speed of the older adults, there were no statistical differences recorded between the age group RMSE, possibly due to gait speed being within the range required for accurate IMU angle measurements. Previous literature has reported gait speeds of 1.0–2.2 m/s have the highest accuracy for IMU sensors, with lower accuracy reported above and below this range [25]. Although the older adults walked, on average, below this threshold it was not enough to affect the RMSE of the IMU. This should be considered when testing in a TKA clinical population, however research has reported very similar gait speeds both pre- and post-surgery compared to the current study [26–28].

Only one study was found that evaluated the accuracy of IMUs when measuring sagittal knee angles in activities other than walking [20]. Our results partially support those of Zhang and colleagues [20], who conducted a comparison of IMU and 3D motion capture technologies across 10 young and healthy individuals. For the sagittal plane Zhang et al. [20] reported the greatest differences between technologies was for the stair descent followed by walking and then stair ascent ($p > 0.05$). In contrast, the results from our study found that walking had the greatest agreement, followed by stair descent, and then stair ascent with the poorest performance. However, like Zhang and colleagues [20] this did not reach statistical significance.

The accuracy of the IMU sensors in comparison to the motion capture varied across the gait cycle. The difference between the measurements was greater during the swing (60–100% gait cycle) versus stance phase (0–60%) for all activities. During the stance phase, the foot is in contact with the ground, and the body's weight is supported by the instrumented leg. This phase typically involves less rapid movement and fewer dynamic changes compared to the swing phase. Consequently, there is less noise and fewer artifacts in the sensor data during this phase given less associated movement of the muscle and underlying tissues. It is thought to lead to more accurate measurements of joint angles of the IMUs as the orientation between the IMU and anatomical coordinate frames is reduced [18,29]. Furthermore, during stance phase there is minimal movement in the frontal and transverse planes increasing accuracy of MotionSense™, and limiting the inaccuracies of the Plug-In-Gait hinge model of the knee joint. Vicon and the Plug-In-Gait model imperfections cannot be ignored, given assumptions made regarding anthropometrics and kinematic joint definitions, as well as variations in marker placement [18]. The Cardan angles of the knee joint determined by motion analysis [30,31] representing flexion–extension, abduction–adduction and internal-external rotation, are not orthogonal. Therefore, significant abduction–adduction or internal-external rotation with high knee flexion may affect the reported knee flexion values; an effect known as cross-talk. This may account for the disparity between the two measurement systems particularly in high degrees of flexion. It should be noted that the soft-tissue artefacts from the MotionSense™ sensors and Vicon passive reflective markers are likely to differ given the size, shape, and placement of each. These differences, in addition to the heterogeneity of participants (e.g. height, fat and muscle tissue, IMU location, and gait technique) has likely driven the variation of error across all participants.

The study presented the findings from a larger cohort of healthy individuals than previously reported, including both younger and older adults, which is a strength of the research. Although the healthy population is expected to be a primary limitation, given the sensors are designed for a TKA clinical, it is not expected that the accuracy in the TKA population will change.

5. Conclusion

MotionSense™ was found to accurately track sagittal knee movement across all activities in both older and younger healthy populations compared to a gold standard Vicon motion capture system. The difference between the technologies may be considered clinically negligible. This conclusion should be verified with a cohort study involving TKA patients, and a feasibility testing of MotionSense™ in a home-based rehabilitation setting using the MotionSense™ package to provide instructional information and real-time feedback at home, and enabling healthcare professionals to continuously monitor rehabilitative progress remotely. This is necessary to highlight the clinical benefit of the technology to aid early discharge, safe monitoring at home, detection for early intervention by improving the patient-clinician dialogue.

Funding

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Ethics approval

This study received NHS R&D approval (IRAS project ID 314702).

Consent to participate

All participants provided informed consent prior to participating in the study. No patient identity is revealed.

CRediT authorship contribution statement

L. Forsyth: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **A. Ligeti:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **M. Blyth:** Writing – review & editing, Methodology, Conceptualization. **J.V. Clarke:** Writing – review & editing, Methodology. **P.E. Riches:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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