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Original Paper

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Can stretch sensors measure knee range of motion in healthy adults?

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Summary

Study aim: There are currently limited methods available to access dynamic knee range of motion (ROM) during free-living activities. This type of method would be valuable for monitoring and progressing knee rehabilitation. Therefore, the aim of this study was to evaluate the functioning of stretch sensors for the measurement of knee ROM and to assess the level of the measurement error.
Material and methods: Nine healthy participants were included in the study. Three stretch sensors (StretchSense™, Auckland, NZ) were attached on the participants' right knees by Kinesiotape®. A Cybex dynamometer was used to standardise movement speed of the knee joint. Data was recorded through the StretchSense™ BLE application. Knee angles were obtained from the video clips recorded during the testing and were analysed by MaxTraq® 2D motion analysis software. The knee angles were then synchronised with the sensor capacitance through R programme.
Results: Seven out of the nine participants presented with high coefficient of determination (R^2)
(>0.98) and low root mean square error (RMSE) (<5°) between the sensor capacitance and knee angle. Two participants did not confirm good relationship between capacitance and knee angle as they presented high RMSE (>5°). The equations generated from these 7 participants' data were used individually to predict knee angles.
Conclusions: The stretch sensors can be used to measure knee ROM in healthy adults during a passive, non-weight-bearing movement with a clinically acceptable level of error. Further research is needed to establish the validity and reliability of the methodology under different conditions before considered within a clinical setting.

Keywords: Rehabilitation – Physical therapy – Joint movement – Dynamic – Functional

Introduction

A variety of techniques and instruments have been developed to measure joint range of motion (ROM). In clinical practice, knee ROM is usually assessed either visually or with a universal goniometer [4]. Plain radiographs have been used to measure pre – and postoperative knee flexion in research studies [4] and computer-assisted navigation has been used to analyse knee ROM during orthopaedic surgery [3]. Radiography currently represents the gold standard for all ROM measurements [14, 21, 23] but this method is expensive, has potentially harmful effects on humans [14], and can only measure static ROM [21]. There have been many studies that have investigated the accuracy, sensitivity and reliability of knee ROM measurement [3, 4, 7, 9, 12, 18, 20, 27]. However, the main limitation of all these measuring methods is that they were static measures of knee ROM and not during functional dynamic activities. Research investigating dynamic ROM assessment is limited and the reliability and validity of dynamic ROM assessment methods remains unclear [10].

Laboratory based equipment such as a dynamometry can be used to collect data regarding angular motion. Even though this type of research yields valuable information, the results only remain valid in conditions where there is no anticipation or reaction to the real environment [6]. Data collection is often in non-weight bearing positions such as sitting and supine that do not reflect functional activities. Laboratory equipment is expensive and not practical in a clinical and rehabilitation scenario [6].

Stretch or flexible sensors are one of the methods that have been used to measure joint ROM [3, 6, 8, 15, 17, 19, 24]. Stretch sensors can deform without breaking and change shape or size in a consistent manner dependent on the forces applied to them. A wide range of materials have been used as stretch sensors to measure human movement range, including thin films of aligned single-walled carbon

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nanotubes; ZnO nanowire/polystyrene hybridized flexible films; electrogoniometers; a mixture of rubber and carbon [6]; conductive rubber; conductive fabrics; polyvinylidene fluoride; and nanocomposites [16, 19]. A stretch sensor network that consists of wireless sensors attached to the patient could, potentially, provide an easy method to collect clinically relevant information about knee function in everyday situations [5]. Bergmann et al., [6] applied stretch sensors integrated into clothing around the knee joint during non-weight bearing movement on a Cybex dynamometer in healthy individuals with the aim of finding a way to measure knee joint kinematics that could be potentially used to detect and manage osteoarthritis (OA). They found an average root mean square error (RMSE) of ~1°, a mean absolute error of ~3° with a coefficient of determination (R^2) above 0.99 between the obtained angles and reference angles. These initial results demonstrated the potential of the sensors to measure dynamic knee ROM in patients with OA that could be used improve patients' quality of life. More recently, Papi et al., [19] demonstrated that a flexible sensor attached to leggings was able to measure peak sagittal knee angles with small margins of error. However, these previous studies have all used sensor systems that were either attached to clothing or orthoses [6, 13, 19] and not directly onto the skin surface of the joint. StretchSense™ (Auckland, NZ) have developed a stretch sensor that combines the ultra softness of silicone with the robustness of a fabric stretch sensor. Each sensor contains an integrated printed circuit board is soft and flexible, allowing the device to conform to the natural curves of the human body. The manufacturer states that the sensor can stretch to up to 3 times (200% strain extension) of it's original length, meaning the sensor should not restrict movements. The capacitance of the sensor changes as the sensor is stretched or compressed. Currently, there are no published studies that have investigated the measurement of knee ROM using stretch sensors attached directly on the skin. Therefore, the aim of this study was to evaluate the functioning of stretch sensors attached on the skin for the measurement of knee ROM and to assess the level of the measurement error.

Materials and methods

Participants

This cross-sectional study included 9 healthy participants both males and females aged 18-40 years. They were selected following the inclusion criteria: no knee pain with any activities, no history of a surgery involving the lower leg, ankle or foot in the last 12 months, no history of an injury to the lower leg, ankle or foot within 6 months, and not allergic to silicone and Kinesiotape.

Testing procedure

The study was approved by the university research ethics committee and all participants provided written informed consent prior to testing. The Kinesiotape was used to attach the sensors to the skin in this study. The tape, a non-restrictive elastic adhesive tape, was selected for use in this study as it can stretch an additional 20-40% of its original length. Importantly, it has been designed to have the same amount of stretch as human skin and to provide support and stability to muscles and joints without restricting ROM [11]. All sensors (StretchSense™, Auckland, NZ) were attached on the participant's right knee with the knee in an extended position. The first sensor without the connector was placed on the tibial tuberosity indicated by palpation and the rest of the sensor was attached over the midpoint of the patella with no tension. The second sensor was placed on the medial side of the knee next to the patella and the third sensor was placed on the lateral side with the middle of both sensors on the tibiofemoral joint line as the ends without the connectors were on the tibia and the other ends were on the femur. Each sensor was directly attached on the skin using a 5-cm-wide Kinesiotape that was placed over the sensor without tension. Two anchor strips (2.5-cm-wide) were placed without tension around the thigh and shank to prevent the sensors from displacing during knee movement (Fig. 1). The Bluetooth communicator was placed on the right thigh and fixed by an elastic bandage (Fig. 1).

A Cybex dynamometer was used to standardise movement speed of the knee joint [6]. Participants were fastened

Fig. 1. Sensor placement for 3 areas and attached on the right knee by Kinesiotape with the Bluetooth communicator fixed by an elastic bandage

to the dynamometer in a sitting position with 3 sensors on the right knee. A mobile phone was set up on a tripod and placed on the medial side of the right leg as a camcorder to record the knee movement. A tablet was used to record sensor capacitance through the StretchSense™ BLE application. For standardisation, the right medial malleolus and the right medial femoral epicondyle were identified and marked by the researcher for knee angle measurement [7] and rechecked by an experienced physiotherapist. The midpoint of the medial side of the femur was marked as a reference for the hip joint as the greater trochanter could not be identified on the medial side (Fig. 2). The dynamometer was set to continuous passive mode (CPM) for a self-selected ROM determined by the participants [6]. To determine ROM, the participants were advised to straighten and bend their knees as much as they could, and those angles were recorded by the Cybex. The participants were given 5 minutes to perform 3 sets of 10 repetitions to familiarise themselves with the dynamometer and to learn to relax their quadriceps when the dynamometer moved. Data collection started when the knee was in an extended position and finished when the knee was fully flexed. The participants repeated the same process 3 times. Data were recorded through the StretchSense™ BLE application when the record button on the tablet screen was pressed and ended when the record button was pressed again.

Knee angles were obtained from the video clips recorded during the testing and were analysed by MaxTraq® 2D motion analysis software (Innovision Systems Inc). The software provided raw data at the rate of 30 frames per second (FPS). Capacitance from the stretch sensors was recorded through the StretchSense™ BLE application installed on the tablet at the rate of 25 FPS. The raw data from both the MaxTraq® and StretchSense™ BLE application were used. Due to the difference in sampling rates between the MaxTraq® and StretchSense™ BLE application, drop frame method was used to reduce the sampling rate to 25 FPS for the MaxTraq® data. The knee angles were then synchronised with the sensor capacitance through R programme.

Statistical analysis

Baseline characteristics of the participants (age, body mass, and height) were expressed as mean±standard deviation (SD). The average of 3 synchronised data sets of knee angles and sensor capacitance from each participant and the average of synchronised data sets from all participants were analysed using JMP® Statistical Software trial version (© SAS Institute Inc.). Scatter plots were created from the average synchronised data set in Excel (Microsoft). Trend lines were also created using a second order polynomial for the curve fit.

Results

Baseline characteristics of the participants are presented in Table 1. Sample size calculations indicated ten participants for the study, however, 9 participants were able to be tested due to changes to the StretchSense™ BLE application. The manufacturer modified the application by removing a function that was essential for the data collection under the study testing protocol.

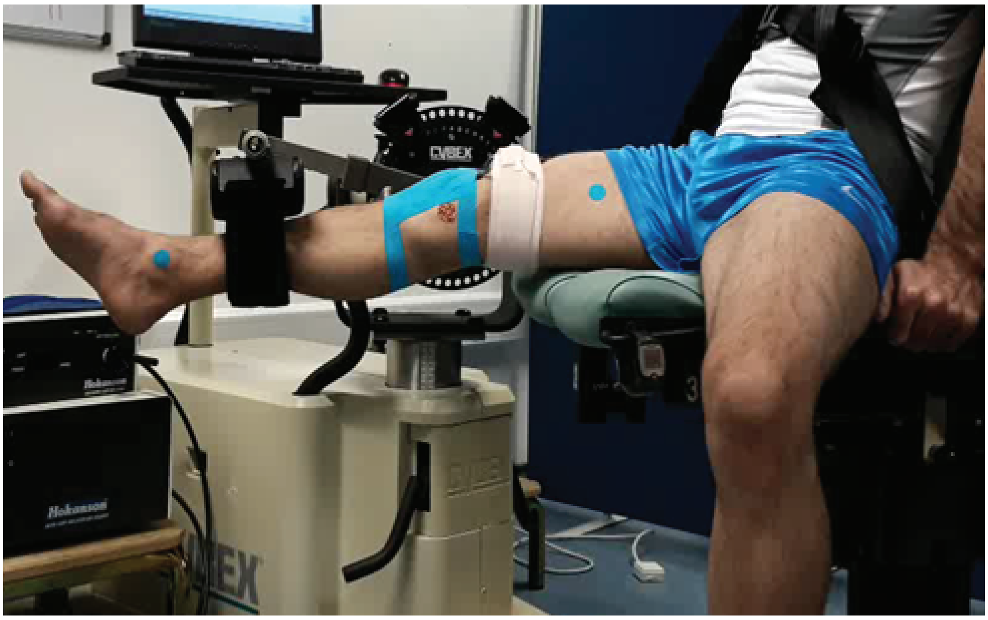

Fig. 2. Three markers used for knee angle measurement

Table 1. Baseline characteristics of the participants

	Male (n = 6)		Female (n = 3)		Total (n = 9)	
	Mean ± SD	Range	Mean ± SD	Range	Mean ± SD	Range
Age [year]	35.5 ± 5.2	26–40	33.7 ± 4.5	29–38	34.9 ± 4.8	26–40
Body mass [kg]	84.3 ± 13.5	70–102	64.0 ± 5.6	59–70	77.6 ± 15.0	59–102
Height [cm]	182 ± 6	176–190	162 ± 3	159–165	175 ± 11	159–190

The capacitance of the sensors was normalised for all participants as they had different starting values. R^2 and RMSE were calculated to determine the robustness of the relationship between the capacitance and the knee angles. The middle sensor demonstrated the highest R^2 and lowest RMSE for seven out of the participants and the results from the middle sensor were therefore selected for further analysis.

Scatter plots of the middle sensor for each participant with trend lines are shown in Figure 3. A nonlinear model was chosen as it had the best fit for the data.

Participant 1 and participant 8 (Fig. 3) presented high RMSE so this did not confirm good accuracy of the sensor on these two participants. Their data were then removed from the analysis. The equations from participants 2 to 7 and participant 9 (Fig. 3) were used to calculate predicted knee angles to compare with actual knee angles as shown in Figure 4. When the mean data set for the 9 participants was analysed, it was not found to be a good fit for nonlinear regression ($R^2 = 0.7864$ and RMSE = 18.00°).

Discussion

The main finding of this study was that there was a strong relationship between the capacitance and knee angles for seven out of the nine participants with high R^2 and a RMSE below 5°. This is clinically important as 5° has been considered as a clinically acceptable level of error in knee angle measurement [1, 25, 26]. However, participant 1 and participant 8 (Figure 3) presented with high RMSE greater than 5°. It is proposed that the reason for the increased RMSE in these two participants was due to the stretch of the sensor [6, 22]. Their graphs show how, at the beginning of knee flexion, the capacitance decreased whilst the knee angle increased which was not expected. This pattern is likely to have been the result of the participant not fully relaxing their leg and the quadriceps contraction causing the change in capacitance.

Figure 4 shows a strong linear relationship between actual knee angles and predicted knee angles with $R^2 > 0.99$ and RMSE <3° for the 7 participants. On the basis of the relationship for these seven participants, there is support for the measurement of knee ROM using stretch sensors attached on the skin on an individual basis. However, it was not possible to produce an overall model for the 7 participants due to the considerable inter-participant variation in the nonlinear regression model for each individual. Anatomical and functional differences could explain the variation in results between participants [2]. Amis et al., [2] found that when the knee was flexed, the patellar translated medially 4 mm to engage the trochlear groove at 20° knee flexion then translated to 7 mm laterally by 90° knee flexion. The patella also tilted progressively to 7° laterally by 90° knee flexion and patellar medial-lateral rotation was usually less than 3°. If there was variation in the distances and of translation and tilting of the patella between individuals, this would have altered the capacitance of the sensor at different points in knee ROM. This would result in the finding of consistent, but varied, nonlinear models for individuals [22]. The implications of this finding is that it may be necessary to calibrate the sensor for every participant before knee angles can be calculated.

Three stretch sensors were placed on different areas of the right knee which were middle, medial, and lateral sides. The medial ($R^2 = 0.7393$; RMSE = 19.80°) and lateral sensors ($R^2 = 0.6193$; RMSE = 23.92°) did not show a strong relationship between sensor capacitance and knee angles. It is likely that the positioning of the sensors on the sides of the patella and over the tibiofemoral joint line resulted in asymmetry between the borders of the sensors as the knee was flexed. That resulted in minimal change in sensor capacitance [6].

This study demonstrated a consistent, strong relationship between capacitance and knee angles in the majority of individuals tested. However, this was for a single application during a passive, non-weight-bearing movement in healthy adults. Future studies need to consider the repeatability of the individual nonlinear regression models, for dynamic weight-bearing movements.

Conclusions

This study was an initial validation study that considered the functioning for stretch sensors attached to the skin

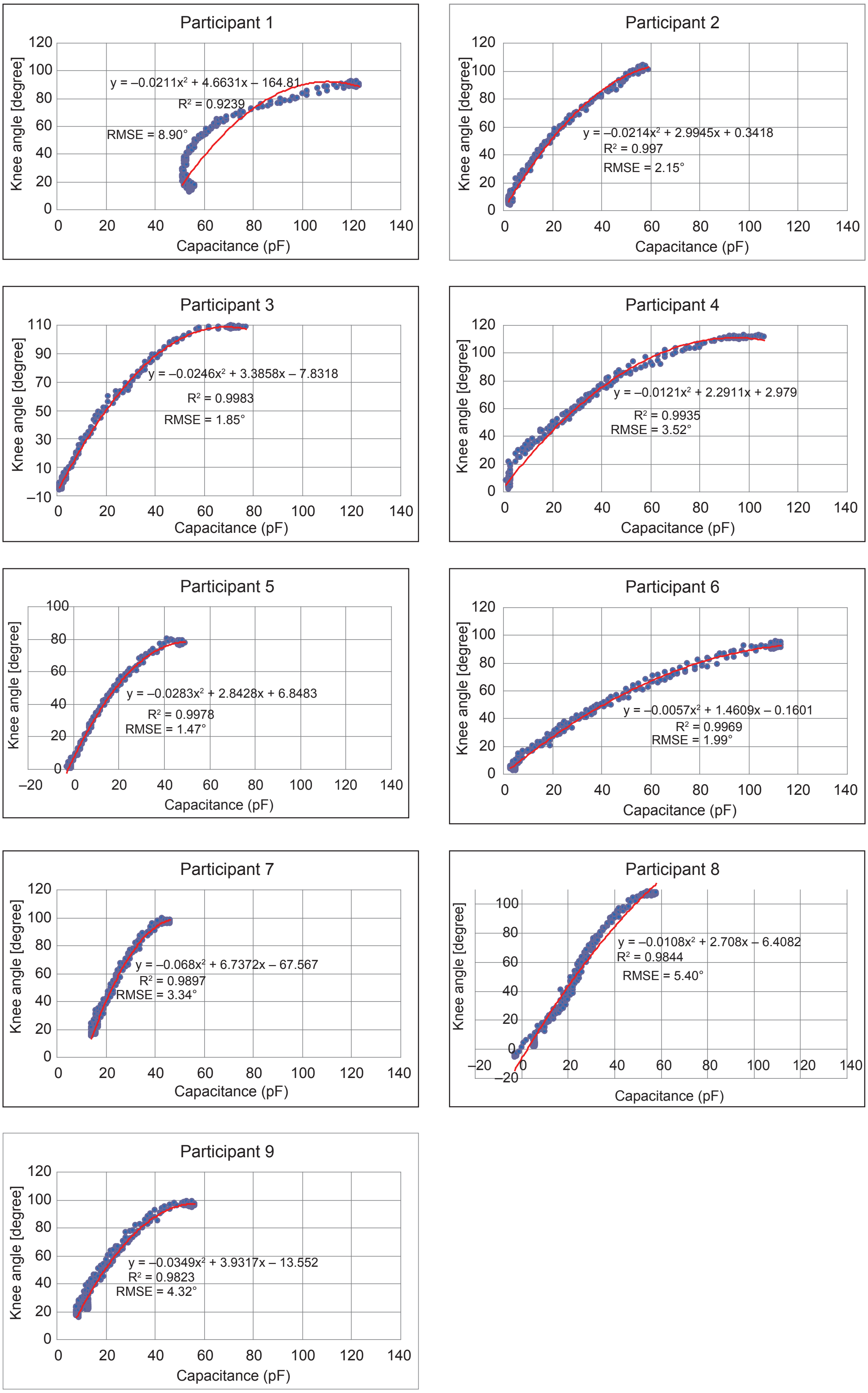

Fig. 3. Individual scatter plots of sensor capacitance and knee angles with the blue dots representing actual relationship between capacitance and knee angles and the red line representing theoretical ideal fit

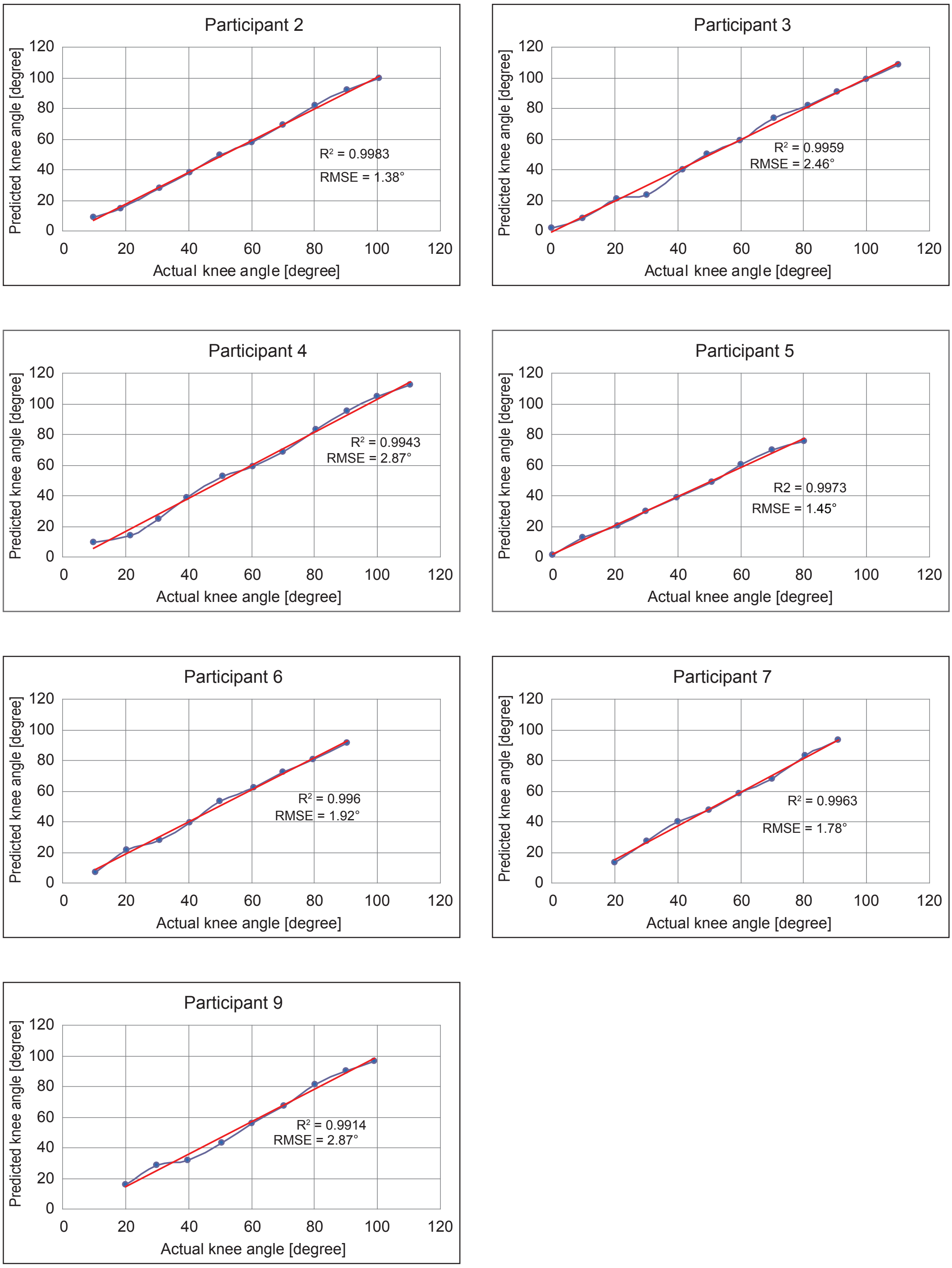

Fig. 4. Individual scatter plots of actual and predicted knee angles with the blue line representing relationship between actual and predicted knee angles and the red line representing theoretical ideal fit

to measure knee ROM. The stretch sensors demonstrated consistent, strong relationships between capacitance and knee angles with less than 5° of error for the majority of participants. On an individual basis in a laboratory situation, it has been shown that it is possible to use stretch sensors to measure knee ROM in healthy adults with a clinically acceptable level of error. Further research is now needed to establish the validity and reliability of the methodology under different conditions before it can be considered within a clinical setting.

Conflict of interest: Authors state no conflict of interest.

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