Test-Retest and Intra-rater Reliability of Using Inertial Sensors and Its Integration with Microsoft Kinect™ to Measure Shoulder Range-of-Motion

Peter Beshara[✉], Judy Chen, Pierre Lagadec, and W.R. Walsh

Physiotherapy Department, Prince of Wales Clinical School, Prince of Wales Hospital, UNSW Australia, High Street, Randwick, Sydney 2031, Australia
{Peter.Beshara,Judy.Chen}@health.nsw.gov.au,
pierre@therealmsystem.com, w.walsh@unsw.edu.au

Abstract. This study determined the intra-rater and test-retest reliability of a novel motion-tracking system that integrates inertial sensors with Microsoft Kinect to measure peak shoulder range-of-motion (ROM) angles. Nine healthy individuals (6 female and 3 male, age: 36.6 ± 13.3) with no shoulder pathology participated following ethical approval. Participants performed active shoulder forward flexion and abduction to the end of available range. Repeat testing of the protocol was completed after 7 days by the same rater. Results demonstrated excellent intra-rater reliability (ICC = 0.84, 0.93) for shoulder flexion and modest-excellent intra-rater reliability (ICC = 0.82, 0.52) for shoulder abduction. A high level of correlation was observed between week 1 and 2 for flexion and abduction (R = 0.85 – 0.93), expect for left abduction (R = 0.60). In conclusion, an inertial system combined with the Kinect is a reliable tool to measure shoulder ROM and has the potential for future research and clinical application.

Keywords: Inertial sensors · Kinematics · Joint angle tracking · Wearable devices · Shoulder

1 Introduction

Shoulder range-of-motion (ROM) measurement in clinical settings is an integral component of physical examination to diagnose, evaluate treatment and quantify possible changes in people with shoulder pain [1]. Compared to any other joint in the body, the shoulder has no fixed axis and produces the greatest ROM in the body. Hence, the reliability of measuring shoulder motion presents a challenge to clinicians.

According to the American Academy of Orthopedic Surgeons, the reported average in adults is 158° for maximal forward elevation and 170° for maximal abduction [2]. Conventionally, shoulder ROM is measured using goniometry and the reliability varies, with intra-class coefficients (ICCs) ranging 0.26 to 0.95 [3–5]. Several other methods have been developed to measure shoulder ROM such as visual estimation [6, 7], still photography [8, 9] and smart-phone applications [10].

Advances in miniature devices and technology have led researchers to utilise wearable inertial sensors to capture human movement. Inertial sensors consisting of accelerometers, gyroscopes and magnetometers have the capability to measure static and dynamic acceleration forces, angular velocity and the strength or direction of geomagnetic or magnetic fields. Inertial sensors have been validated for human joint angle estimation [11, 12] and measurements have shown promising results for various shoulder conditions [13–15]. Furthermore, inertial sensors have demonstrated excellent test-retest reliability (ICC = 0.76) and inter-rater reliability (ICC = 0.84) when measuring elbow flexion in stroke patients [16].

Microsoft Kinect™ (hereafter, simply 'Kinect') is a low cost, portable, motion-sensing device capable of tracking up to six bodies within its field of view. The device features a depth sensor which provides full-body 3D motion capture capabilities. Up to 25 joints positions are extracted in three dimensions for each tracked body. As a markerless system for clinical purposes, it is a favourable alternative to expensive optical systems inside the laboratory environment. To measure shoulder ROM in healthy patients, the Kinect has been compared to goniometry [17], photography [18] and other motion capture systems [19]. One feasibility study with 10 healthy controls reported the Kinect highly reliable (ICC 0.76 – 0.98) for measuring shoulder angles when compared to goniometry and a 3D magnetic tracker [20]. Similarly, excellent agreement between Kinect and goniometry was reported for active shoulder flexion (ICC = 0.86) and abduction (ICC = 0.93) in patients with adhesive capsulitis [21].

The Realm System (Sydney, Australia) combines 2 wireless inertial sensors worn on the wrists with an optical sensor (Kinect v2) to estimate human motion. Optical and inertial data are processed and merged in real-time to produce a full-body kinematic model of the subject. The integration minimises any weaknesses of both individual systems by enabling simpler initialisation procedures, a better visualisation of the estimated angles and better overall precision [22].

However, before such technology can be used routinely, reliability and validity needs to be reviewed to compare its performance to gold standard. Thus, the aim in this study was to determine the test-retest and intra-rater reliability of a system that integrates inertial sensors with Kinect v2 to measure human shoulder joint angles.

2 Methods

2.1 Participants

A convenience sample of nine asymptomatic adults with no history of shoulder pathology (6 female and 3 male, age: 36.6 ± 13.3) performed two shoulder movements according to standardised protocol, together with two raters (A and B). The same nine participants returned 7 days later to assess intra-rater reliability. The study was conducted at the outpatient physiotherapy department at Prince of Wales Hospital, Sydney, Australia. All participants gave their informed consent. The study was approved by the local Ethics Committee.

2.2   Raters

Rater A was a physical therapist of nine years, responsible for wrist sensor placement and initiating the protocol instructions. Rater B was responsible for setting up and executing the inertial motion tracking system with the Kinect. The same raters were used for both assessments.

2.3   Study Procedure

To measure shoulder motion, the system uses 2 WAX9 wireless inertial sensor units (Axivity, UK). The inertial measurement unit (IMU) is a small (23 mm $\times$ 32.5 mm $\times$ 7.6 mm) 9-axis sensor consisting of a 3-axis gyroscope, a 3-axis accelerometer and a 3-axis magnetometer with a Bluetooth Low Energy (BLE) protocol to wirelessly transfer inertial data. The sensors must initially be paired to the receiving computer, and the Bluetooth protocol allows for multiple sensor use. The pairing process allows for identifying and assigning each sensor to a specific part of the body.

Automatic calibration of the system established that the optical sensor (MS Kinect v2) was positioned at a height of 1.40 m and presented a tilt of $-2.0°$. Feet markers were placed at a distance of 2.50 m from the optical sensor to ensure consistency with the initial participant placement. Two IMU's mounted in a wrist band of silicone material were applied around the wrist using the ulnar styloid as a landmark. All participants performed two active motions: shoulder flexion and abduction in the standing position (Fig. 1). Instructions were verbally standardised and participants were asked to move their arm as far as they could. They repeated each motion 3 times at a comfortable speed.

Fig. 1. Experimental setup. The measurement of forward flexion and abduction under instruction from rater.

2.4   Optical and Inertial Data Fusion

Orientation quaternions are calculated on the IMU sensors' microchip at an internal sampling rate of 200 Hz. Joint position data are extracted by the Kinect sensor at a sampling rate of 30 Hz. Both data sets are merged and fed into a full-body kinematic model describing a segmental representation of the skeleton using 16 limbs and 20 joints. The current implementation of the kinematic model ignores fingers and toes segments. The algorithm processing the kinematic model incorporates real-time predictive analysis which relies on the high sampling rate of the IMUs to compensate for the low sampling rate of the Kinect v2 sensor and generate missing positional data when the subject is moving, resulting in the kinematic model being updated at a rate of 100 Hz.

2.5   Calibration and Error Correction

As part of the merging process, optical data from the Kinect v2 sensor is used to further correct any potential drift in the IMU sensors, using forearms positions and a correction weighting of 0.1. This also allows for automatically setting the IMUs' magnetometer heading which cancels the need for initial calibration of the sensors. Optical calibration requires calculating the exact height and tilt angle of the Kinect v2 sensor in order to accurately convert the Kinect's joint position into the kinematic model's 3D reference. Sensor tilt and height can be manually measured and specified in the system configuration. Alternatively, the system allows for automatically calculating these by capturing 3 points on the floor plane and generating the transformation matrix between the detected floor reference system and the kinematic models.

2.6   Shoulder Joint Angle Tracking

The shoulder is part of one of the most complex joints group in the body. The biomechanical model simplifies this complex joint as a ball-and-socket joint with three degrees of freedom (DOF). Due to its markerless nature, the motion capture system extracts the centre of each joint as joint position. Two 3D vectors are extracted from the kinematic model: $\overrightarrow{U_{SE}}$ representing a vector from the shoulder joint center (below the acromion process) to the elbow joint center (between the medial and lateral epicondyles) and $\overrightarrow{U_{SR6}}$ representing a vector from the shoulder joint center to $R6$, defined as a point on the 6th rib along the midaxillary line of the trunk. The position of point $R6$ is derived via projection of the mid spine point of the kinematic model following the trunk and spine orientation. The shoulder angle ∂ is defined in real-time as the angle between the two vectors:

$$\partial = \cos^{-1}\left(\frac{\overrightarrow{U_{SE}} \cdot \overrightarrow{U_{SR6}}}{\|U_{SE}\|\|U_{SR6}\|}\right). \tag{1}$$

The shoulder flexion and extension angles are measured as the value of ∂ while the subject lifts and lowers his extended arm along the sagittal plane. The shoulder abduction and adduction angles are measured as the value of ∂ while the subject lifts and lowers his extended arm along the coronal plane. The neutral position (or zero value) is defined as the moving arm being placed along the lateral mid-line of the humerus in line with the lateral epicondyle.

The position tracking capability of the system has been compared against the gold standard MicroScribe digitizer device (Solution Technologies, Inc.), for the tracking of the wrist, elbow and shoulder joints. Several positions were simultaneously tracked using the system and MicroScribe. Discrepancies were measured by comparing the norm of the movement vectors between sets of static positions tracked by both systems. The average difference found between the system's position tracking and MicroScribe was 2.35 mm. With the MicroScribe device presenting a standard error of 0.23 mm, this strongly indicates that the system is able to accurately track positions in space. Dynamic positional tracking accuracy was established by comparing the system's output to the gold-standard multi-camera Vicon motion capture system (Vicon Motion Systems Ltd.), via a study focusing on dynamic movements. On average, linear regression results of $R = 0.97$ were found across all body joints showing strong correlations between the two systems.

2.7   Statistical Analysis

Data analysis was performed with SPSS version 22 for Windows statistical program. The intra-rater reliability of shoulder flexion and abduction was estimated by using the intraclass correlation coefficient (ICC) model (3,1). This was used as the investigation was an intrarater design with a single rater presenting the only rater of interest. An ICC of ≥ 0.75 was considered as excellent reliability, an ICC of $0.4 - 0.75$ was considered modest reliability, an ICC of <0.4 was considered as poor reliability [23]. Measurement error was expressed in the standard error of measurement (SEM) and minimal detectable change (MDC) was calculated to establish absolute reliability.

$$SEM = SD \times \sqrt{1 - ICC}. \tag{2}$$

$$MDC = SEM \times \sqrt{2} \times 1.96. \tag{3}$$

Test-retest reliability was determined from Pearson's correlation R and the coefficient of determination R^2.

3   Results

3.1   Intra-rater and Test-Retest Reliability

Intra-rater reliability is presented in Table 1. Excellent intra-rater reliability were observed for right flexion, left flexion and right abduction (ICC = 0.84 – 0.93), but results were modest for left abduction (ICC = 0.52). Table 2 presents mean and

standard deviations for week 1 and week 2, R as given by Pearson's product moment correlation and the coefficient of determination R^2. With the exception of left abduction, a relatively high correlation was seen between week 1 and week 2 values for left flexion (R = 0.85), right flexion (R = 0.93) and right abduction (R = 0.89).

Table 1. Intra-rater reliability of the realm system (n = 9)

Motion	$ICC_{3,1}$	95% CI	SEM	MDC
Left flexion	0.84	0.45 – 0.96	1.61	4.47
Right flexion	0.93	0.72 – 0.98	1.16	3.22
Left abduction	0.52	−0.17 – 0.87	2.16	5.99
Right abduction	0.85	0.47 – 0.96	2.45	6.80

Table 2. Mean and standard deviation at Week 1 and Week 2, Pearson's R and coefficient of determination R^2 for both flexion and abduction.

Motion	Week 1 Mean ± SD (°)	Week 2 Mean ± SD (°)	R	R^2
Left flexion	175.80 ± 4.03	176.55 ± 3.50	0.85	0.73
Right flexion	176.10 ± 4.39	174.42 ± 4.15	0.93	0.86
Left abduction	175.05 ± 3.12	174.46 ± 5.46	0.60	0.36
Right abduction	173.72 ± 6.33	174.91 ± 4.64	0.89	0.80

4   Discussion

This study demonstrates that an integrated system of optical and inertial sensors can be a reliable tool to measure ROM of shoulder flexion and abduction. All measurements demonstrated excellent intra-rater reliability expect for left abduction. This can most likely be explained by a general inconsistency in abduction measures observed by the raters. Flexion measures were relatively consistent between and within participants, while abduction was less consistent, predominantly when healthy participants didn't reach peak abduction before lowering their arms. Hence inconsistent measures may be due to an experimental limitation rather than equipment- related error. This study has its limitations as we had a small sample size and did not assess inter-rater reliability, therefore, restricting its applications in clinical settings between observers. Additionally, concurrent validity should be established by comparing measurements to other methods such as goniometry. As a preliminary step to assess the reliability of the Realm System, all participants were healthy, therefore future results need to be replicated in populations of interest, such as those with shoulder pain. This is currently being investigated by the authors of this paper in a clinical randomised control trial for patients awaiting shoulder surgery. In conclusion, the Realm System is reliable to measure shoulder joint angles. Advancements in hardware technology; the miniaturisation of sensors; user-friendly software with Bluetooth technology and simple body-worn sensors makes this method desirable for health clinicians.

References

1. Muir, S.W., Corea, C.L., Beaupre, L.: Evaluating change in clinical status: reliability and measures of agreement for the assessment of glenohumeral range of motion. North Am. J. Sports Phys. Ther. NAJSPT **5**, 98–110 (2010)

2. American Academy of Orthopaedic Surgeons. Joint motion: method of measuring and recording. AAOS, Chicago (1965)

3. Mullaney, M.J., McHugh, M.P., Johnson, C.P., Tyler, T.F.: Reliability of shoulder range of motion comparing a goniometer to a digital level. Physiother. Theory Pract. **26**(5), 327 (2010)

4. Riddle, D.L., Rothstein, J.M., Lamb, R.L.: Goniometric reliability in a clinical setting. Shoulder Measur. Phys. Ther. **67**(5), 668–673 (1987)

5. Hayes, K., Walton, J.R., Szomor, Z.R., Murrell, G.A.: Reliability of five methods for assessing shoulder range of motion. Austr. J. Physiother. **47**(4), 289–294 (2001)

6. Willams, J.G., Callaghan, M.: Comparison of visual estimation and goniometry in determination of shoulder angle. Physiotherapy **76**(10), 655–657 (1990)

7. Terwee, C.B., de Winter, A.F., Scholten, R.J., Jans, M.P., Deville, W., van Schaardenburg, D., Bouter, L.M.: Interobserver reproducibility of the visual estimation of range of motion of the shoulder. Arch. Phys. Med. Rehabil. **86**(7), 1356–1361 (2005)

8. Chen, J.F., Ginn, K.A., Herbert, R.D.: Passive mobilisation of shoulder region joints plus advice and exercise does not reduce pain and disability more than advice and exercise alone: a randomised trial. Austr. J. Physiother. **55**(1), 17–23 (2009)

9. Ginn, K.A., Herbert, R.D., Khouw, W., Lee, R.A.: Randomised controlled trial of a treatment of shoulder pain. Phys. Ther. **77**, 802–809 (1997)

10. Mitchell, K., Gutierrez, S.B., Sutton, S., Morton, S., Morgenthaler, A.: Reliability and validity of goniometric iPhone applications for the assessment of active shoulder external rotation. Physiother. Theory Pract. **30**(7), 521–525 (2014)

11. El-Gohary, M., McNames, J.: Human joint angle estimation with inertial sensors and validation with a robot arm. IEEE Trans. Biomed. Eng. **62**(7), 1759–1767 (2015)

12. Zhou, H., Stone, T., Huosheng, H., Harris, N.: Use of multiple wearable inertial sensors in upper limb motion tracking. Med. Eng. Phys. **30**(I), 123–133 (2008)

13. Coley, B., Jolles, B.M., Farron, A., Bourgeois, A., Nussbaumer, F., Pichonnaz, C., Aminian, K.: Outcome evaluation in shoulder surgery using 3D kinematics sensors. Gait Posture **27**, 368–375 (2007)

14. Luinge, H., Veltink, P., Baten, C.: Ambulatory measurement of arm orientation. J. Biomech. **40**, 78–85 (2007)

15. Teece, R., Lunden, J., Lloyd, A., Kaiser, A., Cieminski, C., Ludewig, P.: Three-dimensional acromioclavicular joint motions during elevation of the arm. J. Ortho. Sports Phys. Ther. **38**(4), 181–190 (2008)

16. Paulis, W.D., Horemans, H.L., Brouwer, B.S., Stam, H.J.: Excellent test-retest and inter-rater reliability for Tardieu Scale measurements with inertial sensors in elbow flexors of stroke patients. Gait Posture **33**(2), 185–189 (2011)

17. Hawi, N., Liodakis, E., Musolli, D., Suero, E.M., Stuebig, T., Claassen, L., Kleiner, C., Krettek, C., Ahlers, V., Citak, M.: Range of motion assessment of the shoulder and elbow joints using a motion sensing input device a pilot study. Technol. Health Care: Offic. J. Eur. Soc. Eng. Med. **22**(2), 289–295 (2014)

18. Matsen III, F.A., Lauder, A., Rector, K., Keeling, P., Cherones, A.L.: Measurement of active shoulder motion using the Kinect, a commercially available infrared position detection system. J. Shoulder Elbow Surg. **25**(2), 216–223 (2016)

19. Nixon, M.E., Howard, A.M, Yu-Ping, C.: Quantitative evaluation of the Microsoft Kinect for use in an upper extremity virtual rehabilitation environment. In: International Conference on Virtual Rehabilitation (ICVR), 26–29 August 2013
20. Huber, M.E., Seitz, A.L., Leeser, M., Sternad, D.: Validity and reliability of Kinect skeleton for measuring shoulder joint angles: a feasibility study. Physiotherapy **101**(4), 389–393 (2015)
21. Lee, S.H., Yoon, C., Chung, S.G., Kim H.C., Kwak, Y., Park, H.W., Kim, K.: Measurement of shoulder range of motion in patients with adhesive capsulitis. PLoS One **10**(6) (2015)
22. Bo, A., Hayashibe, M., Poignet, P.: Joint angle estimation in rehabilitation with inertial sensors and its integration with Kinect. In: 33rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC 2011, pp. 3479–3483. IEEE Press, Boston (2011)
23. Fleiss, J.L.: The Design and Analysis of Clinical Experiments. Wiley Series in Probability and Mathematical statistics Applied Probability and Statistics, p. xiv-432. Wiley, New York (1986)