ARTICLE IN PRESS

Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Short communication

Joint position sense – There's an app for that

Elizabeth S. Edwards, Yin Liang-Lin, Jacqlyn H. King, Andrew R. Karduna*

Department of Human Physiology, University of Oregon, Eugene, Oregon, United States

ARTICLE INFO

Article history:
Accepted 28 July 2016

Keywords:
Proprioception
Joint position sense
Shoulder
Mobile technology
iPod

ABSTRACT

Traditionally, proprioception has been assessed with a passive model, in which an external apparatus moves a body segment. Recently, protocols have been developed based on active movements, which are more representative of functional activities. However, even these approaches require expensive testing equipment and the necessity of a visit to a research lab, as there are no commercially available mobile instruments that allow for the assessment of proprioception outside of a laboratory setting. The objective of this study was to demonstrate the validity and feasibility of using a mobile device (iPod Touch) to assess joint position. We conducted a concurrent validity study in the lab ($n=9$) and a field based study ($n=79$). The field based study was conducted at the 2012 American Society of Biomechanics meeting in Gainesville, Florida. The results of both studies demonstrate good agreement with our established protocol using a magnetic tracking device, with angular errors decreasing with increasing shoulder flexion angles. The studies demonstrate the validity and feasibility of using mobile devices for assessing motion-based parameters, both inside and outside of a laboratory setting.

1. Introduction

Mobile technology is expanding our ability to collect data outside of a laboratory environment, and the field of biomechanics is no exception. Several studies have taken advantage of motion sensors built into smartphones and other mobile devices to assess acceleration (LeMoyne et al., 2013; Wolfgang et al., 2014), physical activity (Bergman et al., 2012; Nolan et al., 2014), gait (Furrer et al., 2015; Sun et al., 2014), posture (Galan-Mercant and Cuesta-Vargas, 2014; Patterson et al., 2014) and range of motion (Bedekar et al., 2014; Mitchell et al., 2014). However, to our knowledge, only one published study has reported using this technology to assess angular kinematics, in which head motion was measured for the purpose of assessing gaze stabilization (Huang et al., 2014).

Previous work from our laboratory has demonstrated that with low angular velocities and accelerations, angular kinematics can be accurately calculated with the use of a triaxial accelerometer (Amasay et al., 2010; Amasay et al., 2009). Since accelerometers and gyroscopes are common in current mobile devices, this technology has the potential for studying mobile-based assessments of motion. The focus of the present study was to demonstrate the ability of a mobile device to assess joint position sense (JPS), which is a sub-modality of proprioception. JPS represents the ability to identify the orientation of a limb in space, in the absence of vision. Many protocols for assessing JPS have used a passive model, in which subjects had their limbs positioned by an external device (Riemann et al., 2002). Our laboratory (Suprak et al., 2006) and other investigators (Langan, 2014; Tripp et al., 2006) have developed protocols based on active movements. However, these approaches require timely setup, the necessity of a visit to a research lab, and expensive testing equipment, such as electromagnetic tracking devices and motion capture systems. There is a need for a more portable device that can be used in a clinical setting (Clark et al., 2015; Hillier et al., 2015; Suetterlin and Sayer, 2014), so that our basic science understanding of proprioception can be translated to clinical practice (Goble, 2010). The purpose of this study was to compare the ability of a mobile device to measure JPS with that of a more established protocol with traditional motion capture equipment. To accomplish this, we performed a concurrent validity study in the lab and a field based study.

2. Methods

2.1. Subjects

For the lab based validity study, nine subjects were recruited from the general university population. There were 6 males and 3 females, with a mean age of 26 years (SD 2), a mean height of 174 cm (SD 5), and a mean body mass of 72 kg (SD 14). Subjects were excluded if they had previous surgery on their shoulder. For the field based study, subjects were recruited from attendees at the 2012 American Society of Biomechanics (ASB) Annual meeting in Gainesville, Florida. A total of 129 subjects were tested (out of 539 attendees). Subjects answered a short questionnaire and any subject with a previous upper extremity injury requiring surgery

* Corresponding author. Fax: +1 541 346 2841.
E-mail address: karduna@uoregon.edu (A. R. Karduna).

http://dx.doi.org/10.1016/j.jbiomech.2016.07.033
0021-9290/

Please cite this article as: S. Edwards, E., et al., Joint position sense – There's an app for that. Journal of Biomechanics (2016), http://dx.doi.org/10.1016/j.jbiomech.2016.07.033

or physical therapy was eliminated from data analysis. Also, any subject who participated in a sport involving overhead activity more than three times a week for more than five years was also excluded from data analysis. This resulted in 79 subjects for analysis (47 male and 32 female), with a mean age of 34 years (SD 11), a mean height of 174 cm (SD 10), and a mean body mass of 74 kg (SD 17). Both studies were approved by the Institutional Review Board at the University of Oregon and all subjects provided informed consent.

2.2. Protocol

Shoulder JPS was assessed with an active joint repositioning task, using an app developed for the 4th generation iPod Touch (Apple, Cupertino, CA). This device has a mass of 100 g, measures 4 cm × 6 cm × 0.6 cm and contains a 3-axis tri-axial accelerometer and a 3-axis gyroscope. The angle of the device with respect to gravity was calculated from the accelerometer data, as we have done previously for an ambulatory tri-axial accelerometer (Amasay et al., 2009). The 95% confidence interval of the accuracy of the iPod Touch to measure acceleration due to gravity is 1% (Khoo Chee Han et al., 2014). The JPS protocol used was a modification of a protocol from our lab in which we used a magnetic tracking device to record kinematics (King et al., 2013). Both protocols assessed JPS during shoulder elevation with the same target angles and number of trials. However, instead of visual cues, the app provides auditory commands to the subject, while subjects kept their eyes closed. Additionally, kinematics are calculated with respect to gravity, rather than with respect to a thoracic sensor (King et al., 2013).

Subjects were in a seated position on a stool with their feet flat on the ground, sitting up straight. The iPod Touch was attached to the lateral side of their dominant humerus with an armband (Fig. 1A). Subjects were instructed on the procedure and allowed practice trials at non-test angles in order for them to become familiar with the protocol. Subjects were told to only move their shoulder, keeping their elbow locked in full extension with their thumb pointing upwards. For the experiment, subjects were presented with three target ranges of shoulder flexion angles: 50°, 70°, and 90°, each plus or minus two degrees (Fig. 1B). Each target position was presented four times for a total of 12 trials, which were randomized.

At the start of a trial, there was a low frequency tone, which indicated that the shoulder was below the target range (eg., 48°). When the subject elevated their arm into the target range (eg., 48°–52°), the tone was silenced. If the subject overshoot the range (eg., 52°), then there was a high frequency tone. Subjects continued to adjust their elevation angle (increased elevation if there was a low tone and decreased elevation if there was a high tone), until they were in the target range (no sound). They had previously been instructed to memorize their arm position during this time. After the position had been held for two seconds, the subjects were prompted by a "relax" cue, which instructed them to return to the starting position (arm at the side). After three seconds, they were instructed to "find target," at which point they attempted to replicate the target angle they had just memorized. The device recorded their repositioned angle when their velocity was less than 0.25 deg/sec for a one second time period. Once the testing for a given angle had finished, the subject was automatically prompted on to the next trial. The differences between the actual angle reached with auditory cues and the repositioned angle, with no auditory cues, were calculated and the constant and variable errors and was used for analysis (Schmidt and Lee, 2005). As noted above, the actual angle was always within two degrees of the target angle.

For the field based study, only the iPod Touch was used. To help facilitate the collection of data from as many subjects as possible, three subjects were tested simultaneously. For the lab based study, subjects were also instrumented with a Liberty magnetic tracking device (Polhemus, Colchester, VT), as described previously (Lin and Karduna, 2016). Sensors were mounted on the manubrium of the sternum, the flat area of the acromion, and on the distal humerus via a custom-molded cuff. Anatomic landmarks were palpated and digitized, using the standards recommended by the International Society of Biomechanics (ISB) (Wu et al., 2005). Kinematic data were converted from sensor coordinate systems to anatomic coordinate systems. The JPS protocol was performed exactly the same as the field based study, with the exception that kinematics data were collected simultaneously from the iPod Touch and the magnetic tracking device. Errors were calculated from both sets of kinematics data.

2.3. Statistical analysis

SPSS version 23 (IBM, Chicago IL) was used for statistical analysis. For the lab based study, we performed paired *t*-tests, comparing constant and variable errors between the iPod Touch and magnetic tracking devices at each target angle (50°, 70°, and 90°). For the field based study, we performed a one-way repeated measures analysis of variance (ANOVA) with target angle (50°, 70°, and 90°) as the independent variable and constant and variable errors as the dependent variables. Pairwise comparisons were performed when a significant main effect was found with the ANOVA. Additionally, the data were qualitatively compared with the results from our previous lab-based study of JPS (King et al., 2013).

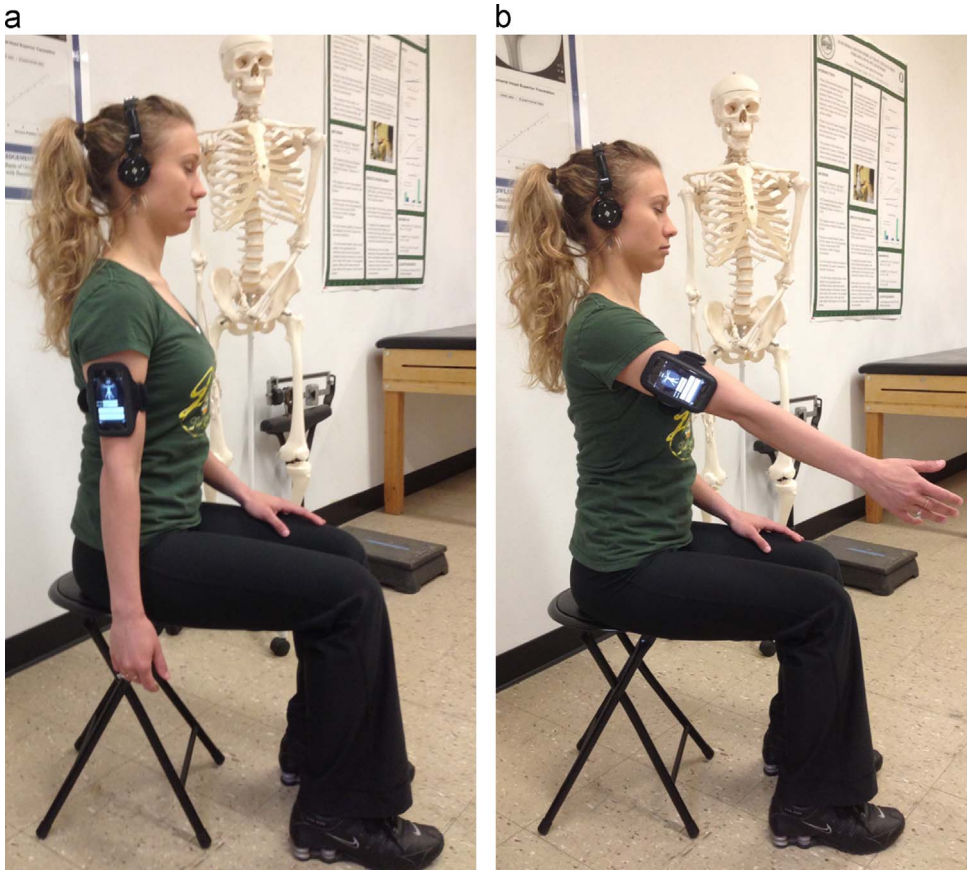

Fig. 1. Picture of subject during testing protocol with iPod Touch mounted on the arm. A) Shoulder at the side. B) Reaching for target.

Please cite this article as: S. Edwards, E., et al., Joint position sense – There's an app for that. Journal of Biomechanics (2016), http://dx.doi.org/10.1016/j.jbiomech.2016.07.033

3. Results

For the lab based study, there were no significant differences at any angles for both the constant errors ($p > 0.40$) and variable errors ($p > 0.05$). The differences between the mean errors calculated with the iPod Touch and magnetic tracking device range from 0.1°–0.4° (Fig. 2).

For the field based study, the results from the ANOVA demonstrated a significant effect of target on constant error ($p < 0.001$) and variable error ($p = 0.025$). Follow-up pairwise comparisons revealed that constant errors at 50° ($M = 4.5°$) were significantly larger than errors at 70° ($M = 2.8°$) and 90° ($M = 2.3°$). Similarly, variable errors at 50° ($M = 2.4°$) were significantly larger than errors at 70° ($M = 2.1°$) and 90° ($M = 2.0°$). These data are similar to our previous study (King et al., 2013), both in terms of the value of the errors, and the general shape of the response (Fig. 3).

4. Discussion

With the exception of low tech options, like goniometers (Vafadar et al., 2015), inclinometers (Dover et al., 2003), and laser pointers (Balke et al., 2011), quantitative assessments of proprioception have largely remained limited to laboratory settings. The long-term goal of this project is to evaluate an inexpensive, portable and relatively quick method for the assessment of proprioception that would be applicable in both a clinical and research setting. Such an instrument would be useful in allowing larger scale proprioception questions to be addressed. The main objectives of the current study were to demonstrate the validity and feasibility of using an iPod Touch.

Despite the numerous differences in kinematic assessment for the iPod Touch (eg., greater mass, no thoracic sensor, gravity based) when compared to a magnetic tracking device, our lab based validation study demonstrated remarkable agreement between the two approaches. It should be noted that this was a concurrent validity study, so that the kinematic data were collected simultaneously from both techniques, but that the iPod Touch was used to guide the subject. An alternative approach would have been to assess the subjects independently with an iPod Touch and then again with a magnetic tracking device. It is also important to note that this study was designed to validate the outcome measures (JPS error) of the iPod Touch. It was not designed to validate the general ability of the iPod touch to assess joint kinematics.

We were able to collect data on 129 subjects over a three-day period at the 2012 ASB meeting. This short time frame is unrealistic for most lab-based studies of JPS. We were able to test a large number of subjects because of the short data collection and the fact that we were able to collect data from three subjects simultaneously. There were no safety or technical complications that prevented us from collecting data on any of the subjects. The convenience afforded by the iPod Touch for the collection of large-scale data sets over short intervals makes it ideal for collecting field-based data, for example at an athletic event or a nursing home. The results in the present study are consistent with previous work from our laboratory (King et al., 2013; Suprak et al., 2006) and others (Balke et al., 2011; Hung and Darling, 2012; Vafadar et al., 2015) that demonstrated that as shoulder targets approached 90° of elevation, the errors of joint repositioning decreased. The present study demonstrated a similar pattern although with a larger subject population. When compared to King et al. (2013), which used the same shoulder motion (flexion) and same targets (50°, 70° and 90°), not only was there a similar trend observed, but the errors at each of the target angles were similar in magnitude, with less than a one degree of deviation (Fig. 2).

Mobile devices have been used to asses joint angles during static tasks at the spine (Bedekar et al., 2014), elbow (Ferriero et al., 2011), knee (Jenny et al., 2015), wrist (Kim et al., 2014), shoulder (Johnson et al., 2015), and foot (Otter et al., 2015). In fact, there are several commercial apps available on the iTunes store that are specifically designed for clinicians or researchers to assess joint angles (eg, DrGoniometer, Simple Goniometer, GetMyROM, Knee Goniometer). However, we are not aware of any application in which the dynamic assessments of joint motion can be incorporated into the app. Although the focus of the present study was on shoulder JPS, we have also utilized this app for assessing JPS of the elbow, wrist, knee and ankle and are optimistic that the app has utility for multiple joints.

With the efficacy that this device provides, it not only allows more data to be collected, but also allows the potential for wider ranges of studies to be performed. In addition to allowing for a large subject pool to be collected, wireless transmission of accelerometer data is possible. We used a cloud-based service (Dropbox, San Francisco, CA) to view the data from a trial within 15 s of it being collected, which allowed for the verification of proper completion of the trial and also supplied immediate data response. Furthermore, the device is portable, as well as efficient and easy to use. The iPod Touch also provided verbal commands through wireless headphones. These commands would allow for other types of vibrotacile and auditory feedback to be used. For example,

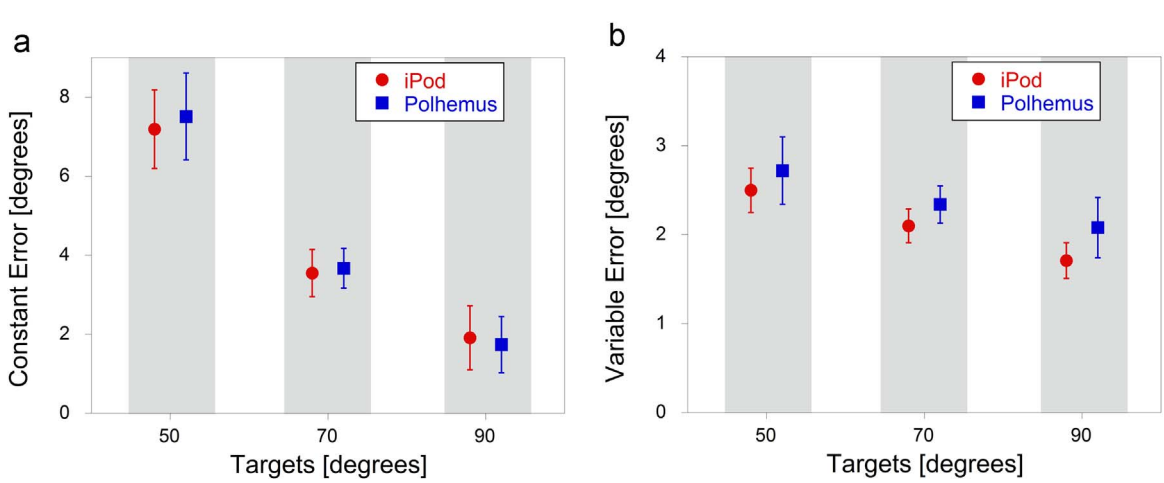

Fig. 2. A) Constant errors and B) variable errors for the lab based validation study. Data are plotted vs target angle for both the iPod Touch and Polhemus kinematics measurements. Data represent means ± standard error of the means.

Please cite this article as: S. Edwards, E., et al., Joint position sense – There's an app for that. Journal of Biomechanics (2016), http://dx.doi.org/10.1016/j.jbiomech.2016.07.033

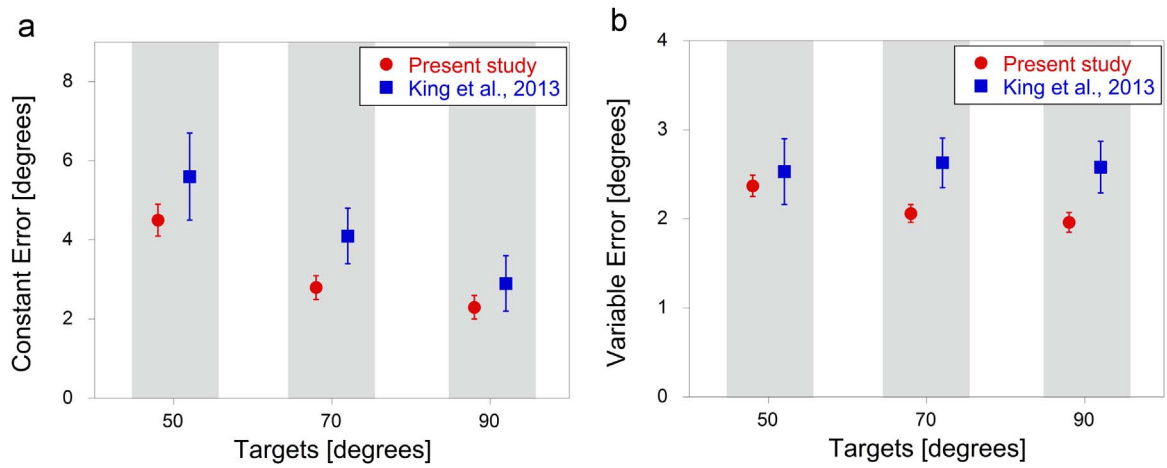

Fig. 3. A) Constant errors and B) variable errors for the field based study. Data are plotted vs target angle for the present study, compared with those of King et al., 2013. Data represent means ± standard error of the means.

an iPhone was used to deliver vibrotacile feedback, in assistance with balance positioning (Lee et al., 2012). Our JPS app along with other apps could be useful in the assessment of ROM, biofeedback and training tools. We chose to use an iPod Touch because we did not need cellular data; however, the app will work equally well on an iPhone. Future versions could be targeted for Android based devices.

It is important to acknowledge several limitations to this present study. Firstly, because this is an ipsilateral remembered task, this protocol may not be suitable for patients with short term memory deficits (Goble, 2010). This would likely be more of a concern to patients with neurological, as opposed to musculoskeletal pathologies. Another consideration is that the device measured angles with respect to gravity. Therefore, since the device was attached to the humerus, we were unable to consider or calculate the sway of the trunk. Traditional JPS studies are able to account for trunk sway due to their ability to attach multiple devices to the body. Finally, with the current version of the app, we can only use an ipsilateral remembered model. However, it is technically possible to link two devices together, which would allow for a contralateral matching model to be used.

5. Conclusions

The results of the present study of JPS with an iPod touch was found to be consistent with assessment made with a magnetic tracking device, demonstrating that subjects had the highest errors at 50° of shoulder flexion, with errors decreasing as flexion angles increased. The iPod Touch provides an ideal platform for a quick and in-expensive assessing joint position sense.

Conflict of interest

There are no known conflicts of interest associated with this work. Specifically, there are no financial or personal relationships with other people or organizations that could inappropriately influence or bias this work.

Acknowledgments

Funding was provided by a University of Oregon 2012 Summer Research Award. The mobile app was developed in conjunction with Dana Maher, from the University of Oregon's InfoGraphics Lab (infographics.uoregon.edu). Finally, the authors would like to thank the American Society of Biomechanics for the opportunity to collect data at its annual meeting.

References

Amasay, T., Latteri, M., Karduna, A.R., 2010. In vivo measurement of humeral elevation angles and exposure using a triaxial accelerometer. Hum. Factors 52, 616–626.
Amasay, T., Zodrow, K., Kincl, L., Hess, J., Karduna, A., 2009. Validation of tri-axial accelerometer for the calculation of elevation angles. Int. J. Ind. Ergon. 39, 783–789.
Balke, M., Liem, D., Dedy, N., Thorwesten, L., Balke, M., Poetzl, W., Marquardt, B., 2011. The laser-pointer assisted angle reproduction test for evaluation of proprioceptive shoulder function in patients with instability. Arch. Orthop. Trauma Surg. 131, 1077–1084.
Bedekar, N., Suryawanshi, M., Rairikar, S., Sancheti, P., Shyam, A., 2014. Inter and intra-rater reliability of mobile device goniometer in measuring lumbar flexion range of motion. J. Back Musculoskelet. Rehabil. 27, 161–166.
Bergman, R.J., Spellman, J.W., Hall, M.E., Bergman, S.M., 2012. Is there a valid app for that? Validity of a free pedometer iPhone application. J. Phys. Act. Health 9, 670–676.
Clark, N.C., Roijezon, U., Treleaven, J., 2015. Proprioception in musculoskeletal rehabilitation. Part 2: clinical assessment and intervention. Man. Ther. 20, 378–387.
Dover, G.C., Kaminski, T.W., Meister, K., Powers, M.E., Horodyski, M., 2003. Assessment of shoulder proprioception in the female softball athlete. Am. J. Sport Med. 31, 431–437.
Ferriero, G., Sartorio, F., Foti, C., Primavera, D., Brigatti, E., Vercelli, S., 2011. Reliability of a new application for smartphones (DrGoniometer) for elbow angle measurement. PM&R 3, 1153–1154.
Furrer, M., Bichsel, L., Niederer, M., Baur, H., Schmid, S., 2015. Validation of a smartphone-based measurement tool for the quantification of level walking. Gait Posture 42, 289–294.
Galan-Mercant, A., Cuesta-Vargas, A.I., 2014. Mobile Romberg test assessment (mRomberg). BMC Res. Notes 7, 640.
Goble, D.J., 2010. Proprioceptive acuity assessment via joint position matching: from basic science to general practice. Phys. Ther. 90, 1176–1184.
Hillier, S., Immink, M., Thewlis, D., 2015. Assessing proprioception: a systematic review of possibilities. Neurorehabil. Neural Repair 29, 933–949.
Huang, K., Sparto, P.J., Kiesler, S., Siewiorek, D.P., Smailagic, A., 2014. iPod-based in-home system for monitoring gaze-stabilization exercise compliance of individuals with vestibular hypofunction. J. Neuroeng. Rehabil. 11, 69.
Hung, Y.J., Darling, W.G., 2012. Shoulder position sense during passive matching and active positioning tasks in individuals with anterior shoulder instability. Phys. Ther. 92, 563–573.
Jenny, J.Y., Bureggah, A., Diesinger, Y., 2015. Measurement of the knee flexion angle with smartphone applications: Which technology is better? Knee Surg. Sports Traumatol. Arthrosc. [Epub ahead of print]
Johnson, L.B., Sumner, S., Duong, T., Yan, P., Bajcsy, R., Abresch, R.T., de Bie, E., Han, J. J., 2015. Validity and reliability of smartphone magnetometer-based goniometer evaluation of shoulder abduction - A pilot study. Man. Ther. [Epub ahead of print]
Khoo Chee Han, C., Shanmugam, R.A., Choon Siew Kit, D., 2014. Accuracy, consistency, and reproducibility of the triaxial accelerometer in the iPod touch: a pilot study. JMIR mhealth uhealth 2, e39.

Kim, T.S., Park, D.D., Lee, Y.B., Han, D.G., Shim, J.S., Lee, Y.J., Kim, P.C., 2014. A study on the measurement of wrist motion range using the iPhone 4 gyroscope application. Ann. Plast. Surg. 73, 215–218.

King, J., Harding, E., Karduna, A., 2013. The shoulder and elbow joints and right and left sides demonstrate similar joint position sense. J. Mot. Behav. 45, 479–486.

Langan, J., 2014. Older adults demonstrate greater accuracy in joint position matching using self-guided movements. Hum. Mov. Sci. 36, 97–106.

Lee, B.C., Kim, J., Chen, S., Sienko, K.H., 2012. Cell phone based balance trainer. J. Neuroeng. Rehabil. 9, 10.

LeMoyne, R., Mastroianni, T., Grundfest, W., Nishikawa, K. 2013. Implementation of an iPhone wireless accelerometer application for the quantification of reflex response. In: Proceedings of the Conference IEEE Engneering in Medicine and Biololgy Society. pp. 4658–4661.

Lin, Y.L., Karduna, A., 2016. A four-week exercise program does not change rotator cuff muscle activation and scapular kinematics in healthy subjects. J. Orthop. Res.

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

Nolan, M., Mitchell, J.R., Doyle-Baker, P.K., 2014. Validity of the Apple iPhone(R) /iPod Touch(R) as an accelerometer-based physical activity monitor: a proof-of-concept study. J. Phys. Act. Health 11, 759–769.

Otter, S.J., Agalliu, B., Baer, N., Hales, G., Harvey, K., James, K., Keating, R., McConnell, W., Nelson, R., Qureshi, S., Ryan St, S., John, A., Waddington, H., Warren, K., Wong, D., 2015. The reliability of a smartphone goniometer application compared with a traditional goniometer for measuring first metatarsophalangeal joint dorsiflexion. J. Foot Ankle Res. 8, 30.

Patterson, J.A., Amick, R.Z., Thummar, T., Rogers, M.E., 2014. Validation of measures from the smartphone sway balance application: a pilot study. Int. J. Sport. Phys. Ther. 9, 135–139.

Riemann, B.L., Myers, J.B., Lephart, S.M., 2002. Sensorimotor system measurement techniques. J. Athl. Train. 37, 85–98.

Schmidt, R.A., Lee, T.D., 2005. Motor Control and Learning: A Behavioral Emphasis, 4th ed. Human Kinetics, Champaign.

Suetterlin, K.J., Sayer, A.A., 2014. Proprioception: where are we now? A commentary on clinical assessment, changes across the life course, functional implications and future interventions. Age Ageing 43, 313–318.

Sun, B., Wang, Y., Banda, J., 2014. Gait characteristic analysis and identification based on the iPhone's accelerometer and gyrometer. Sensors 14, 17037–17054.

Suprak, D.N., Osternig, L.R., van Donkelaar, P., Karduna, A.R., 2006. Shoulder joint position sense improves with elevation angle in a novel, unconstrained task. J. Orthop. Res. 24, 559–568.

Tripp, B.L., Uhl, T.L., Mattacola, C.G., Srinivasan, C., Shapiro, R., 2006. A comparison of individual joint contributions to multijoint position reproduction acuity in overhead-throwing athletes. Clin. Biomech. 21, 466–473.

Vafadar, A.K., Cote, J.N., Archambault, P.S., 2015. Inter-rater and intra-rater reliability and validity of three measurement methods for shoulder position sense. J. Sport Rehabil.

Wolfgang, R., Di Corleto, L., Burgess-Limerick, R., 2014. Can an iPod Touch be used to assess whole-body vibration associated with mining equipment? Ann. Occup. Hyg. 58, 1200–1204.

Wu, G., van der Helm, F.C., Veeger, H.E., Makhsous, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion–Part II: shoulder, elbow, wrist and hand. J. Biomech. 38, 981–992.

Please cite this article as: S. Edwards, E., et al., Joint position sense – There's an app for that. Journal of Biomechanics (2016), http://dx.doi.org/10.1016/j.jbiomech.2016.07.033