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ORIGINAL ARTICLE

Mobile technology and telemedicine for shoulder range of motion: validation of a motion-based machine-learning software development kit

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Background: Mobile technology offers the prospect of delivering high-value care with increased patient access and reduced costs. Advances in mobile health (mHealth) and telemedicine have been inhibited by the lack of interconnectivity between devices and software and inability to process consumer sensor data. The objective of this study was to preliminarily validate a motion-based machine learning software development kit (SDK) for the shoulder compared with a goniometer for 4 arcs of motion: (1) abduction, (2) forward flexion, (3) internal rotation, and (4) external rotation.
Methods: A mobile application for the SDK was developed and "taught" 4 arcs of shoulder motion. Ten subjects without shoulder pain or prior shoulder surgery performed the arcs of motion for 5 repetitions. Each motion was measured by the SDK and compared with a physician-measured manual goniometer measurement. Angular differences between SDK and goniometer measurements were compared with univariate and power analyses.
Results: The comparison between the SDK and goniometer measurement detected a mean difference of less than 5° for all arcs of motion ($P > .05$), with a 94% chance of detecting a large effect size from a priori power analysis. Mean differences for the arcs of motion were: abduction, −3.7° ± 3.2°; forward flexion, −4.9° ± 2.5°; internal rotation, −2.4° ± 3.7°; and external rotation −2.6° ± 3.4°.
Discussion: The SDK has the potential to remotely substitute for a shoulder range of motion examination within 5° of goniometer measurements. An open-source motion-based SDK that can learn complex movements, including clinical shoulder range of motion, from consumer sensors offers promise for the future of mHealth, particularly in telemonitoring before and after orthopedic surgery.
Level of evidence: Basic Science Study; Development or Validation of Outcome Instrument

Keywords: Shoulder; range of motion; mHealth; software development kit (SDK); telemedicine; motion-based machine-learning

This study was exempt from Insitutional Review Board approval (IRB #17-800, exemption).

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The recent focus on value-based health care and the commoditization of technologically advanced consumer devices, from smartphones to wearables (ie, Fitbit [San Francisco, CA, USA], Apple Watch [Apple, Cupertino, CA, USA],

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and Jawbone [San Francisco, CA, USA]), offers a unique opportunity to harmonize orthopedic care teams to evaluate activity and motion-related data.[3,11,13,15] The field of mobile health, or mHealth, has generated great interest with the capacity for everyday devices to passively store a tremendous amount of personal health data (ie, step count and stairs climbed).[2,6,12,14,18] However, the current mHealth landscape is fragmented, lacking interoperability between the myriad of devices and applications. Ramkumar et al[24] described the tremendous opportunity available to orthopedic surgeons with open-source software that leverages native sensors of mobile devices, particularly the accelerometer, gyroscope, and magnetometer, that can be processed, analyzed, and contextualized regardless of platform or device.

Although general activity data remain an accessible objective end point for lower extremity procedures, open-source software that analyzes the greater degrees of freedom available for the upper extremities remains elusive.[17,20] Furthermore, to the best of our knowledge, no hardware or software facilitating remote telemonitoring of specific, complex spatial tasks for the lower or upper extremity required in preoperative and postoperative rehabilitation exists to assess patient compliance.

In recent years, there has been growth in the use of software development kits (SDKs) to design open-source technology that may be incrementally updated.[16,22] SDKs have the capability of machine learning, allowing the software to automate processes through artificial intelligence and pattern recognition from empirical data.[10,26] The advances in the sensors of modern smartphones and wearables have permitted the development of a proprietary SDK that gathers user data passively to filter and process complex data, to "learn" a given motor task after minimal repetitions, to assess compliance for both repetitions and form, and then to report feedback with real-time analysis.[1,23] The value of an SDK that can learn complex spatial movements, including the clinical examination for shoulder range of motion (ROM), may portend favorable adoption of telemedicine by reducing the amount of time patients spend accessing care while simultaneously cutting systemic costs and improving physician efficiency for additional health care delivery.[8,9,25]

Clinically, the ability of this technology to grossly detect shoulder motion offers the newfound ability to determine whether a patient is compliant, and to what degree, with a prescribed home stretching and strengthening program in an outpatient setting. Further, validation of accuracy offers real-time, intraoperative angular feedback to the surgeon and may lend to cost-effective navigation procedures using inexpensive commercial sensors. To payers and researchers, the ability to document functional and symptomatic improvements preoperatively to postoperatively on a more continuous basis offers the opportunity to assess outcomes with increased granularity and consistency, which leads to capturing value of care delivered.

There has been no open-source scalable SDK capable of learning and analyzing complex spatial motion developed or validated in the clinical setting to our knowledge. The SDK presents a new opportunity to have a patient remotely perform objective components of the orthopedic physical examination using any personal mobile device, from an Android (Google, Menlo Park, CA, USA) phone to an Apple Watch. Further, if able to "learn" the ROM maneuvers of the shoulder, future activities and exercises may be subsequently learned and customized to the patient's preoperative and postoperative regimen. Thus, the objective of the present study was to validate a proprietary open-source motion-based machine learning SDK in a joint with many degrees of freedom, specifically the shoulder, by way of assessing the angular accuracy compared with a manual goniometer for the following arcs of motion: (1) abduction, (2) forward flexion, (3) internal rotation, and (4) external rotation.

Materials and methods

This clinical study, which was registered on ClinicalTrials.gov (NCT03195751), assessed the accuracy of an SDK in measuring ROM in 10 healthy participants who were prospectively enrolled and performed the following 4 shoulder ROM maneuvers 5 times each: abduction, forward flexion, internal rotation, external rotation. After each degree of arc self-directed by the participant, the angular measurements were taken by the manual goniometer and software.

Core software technology

The SDK (FocusMotion, Santa Monica, CA, USA) processes user motions recorded by the hardware (ie, accelerometer, gyroscope, and magnetometer) present in common smartphones (ie, Apple iPhone, Google Android) and wearable devices.[4,29] As the user completes an exercise or routine, the SDK passively tracks the number of repetitions performed, techniques, and rest times.[4] The SDK can provide real-time feedback to the user regarding his or her form by comparing the movement to a template of an ideal motion for that particular action.[4] For the purpose of this study, the hardware selected to test the SDK was an iPhone for the advanced sensors, Bluetooth (Bluetooth SIG, Inc., Kirkland, WA USA) capability, and simplicity of developing a mobile application or "app" with a facile user experience. The app was designed and securely installed on a single secure smartphone to serve as a private user interface for the proprietary SDK. Thus, the system was created to allow native iPhone sensors to feed spatial data directly to the SDK with movement. The SDK uses the raw data from the built-in iPhone sensors (ie, accelerometer, gyroscope), contextualizes it in the context of the "learned" arc of shoulder motion for each participant, and outputting a ROM from these measurements after processing. For the SDK to learn and process the new activity before initiating remote testing on participants, 5 repetitions with the iPhone strapped to the lead author (P.N.R.) using an armband were performed for each of the 4 shoulder maneuvers. The app used a Bluetooth connection to pair with a smartwatch to allow for remote timekeeping of the smartphone while in use by the participant.

Participants

Participants responded to printed fliers on the campus of the lead author's institution. Individuals without shoulder pain, with full