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Research Paper

Software-based finger joint range of motion analysis: Current concepts, considerations, and challenges

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ABSTRACT

Background: Finger and wrist joint range of motion (ROM) measurement are key parameters of the hand examination and contribute to the diagnosis and monitoring of hand pathology. Technology-based ROM measurement tools, particularly software-based systems such as image analysis systems or augmented reality–based measurement, have potential to facilitate efficient ROM measurement in both virtual and in-person settings.
Purpose: The purpose of this paper is to provide some knowledge translation of available and prospective technologies from developer to clinician literature. Specifically, this article aimed to define the landscape of current software-based ROM analysis systems; discuss considerations and challenges inherent in the development of software-based technologies; and propose future directions for integration of software-based ROM analysis systems into clinical practice. Software-based motion analysis systems fall into two large categories: image analysis software and augmented reality–based hand tracking applications. Ongoing development of software-based systems range from opportunities and pitfalls associated with use of open-source frameworks. Therapists and surgeons considering use or development of software-based systems will need to establish the reliability and validity of ROM measurement, ensure accessibility across socioeconomic diverse populations, understand the impact of patient-driven ROM measurement, and consider appropriate regulatory body approval. Future directions for development entail the integration of artificial intelligence frameworks into existing software-based systems for optimization of measurement and pattern recognition as well as adoption of software-based measurement into in-person care in addition to telerehabilitation.
Conclusions: As software-based motion analysis systems are further refined with patient and therapist needs at the forefront of development, such tools have the potential to optimize the provision of hand therapy while empowering patients to be involved in their own care.

Background

Finger and wrist joint range of motion (ROM) is central to the proper functioning of the hand and, therefore, is a central component of the hand examination.[1,2] ROM measurements can be used to inform diagnoses, post-intervention progress, or rehabilitation goals. Manual goniometry using a protractor-based goniometer placed on the dorsum of the hand is the most commonly reported means of measuring finger joint ROM.[3] While this method possesses the advantages of being simple to use and relatively inexpensive, its drawbacks as a measurement tool include its reliance on user experience for intra-rater reliability and the need for inter-user agreement on methods to produce similar results.[4,5] Additionally, physical factors such as atypical anatomy, tremors, and wounds pose additional challenges to goniometric measurements.[5] Technologic advances in ROM analysis represent an opportunity to overcome some of these challenges. The last three decades have heralded the development of technology-based means of measuring finger joint ROM using sensor- or glove-based measurement, optoelectronic motion analysis, markerless depth-based cameras, photography-based ROM measurement, and computer vision-based assessment of ROM. While some of these technologies aim to provide more efficient measurement tools, other systems intend to improve the accuracy of finger joint ROM by reducing human-introduced measurement error.

A significant consideration in the development of technology-based joint motion analysis is the practicality of such devices for clinical use, both in the in-person setting and for remote care encounters, often referred to as "telerehabilitation." Technology-based ROM capture devices can be largely categorized into two groups: systems requiring specific hardware and those with software-only capability (Fig. 1). In this article, we refer to proposed methods of ROM analysis with a "hardware" component as any technology-based ROM analysis system requiring a

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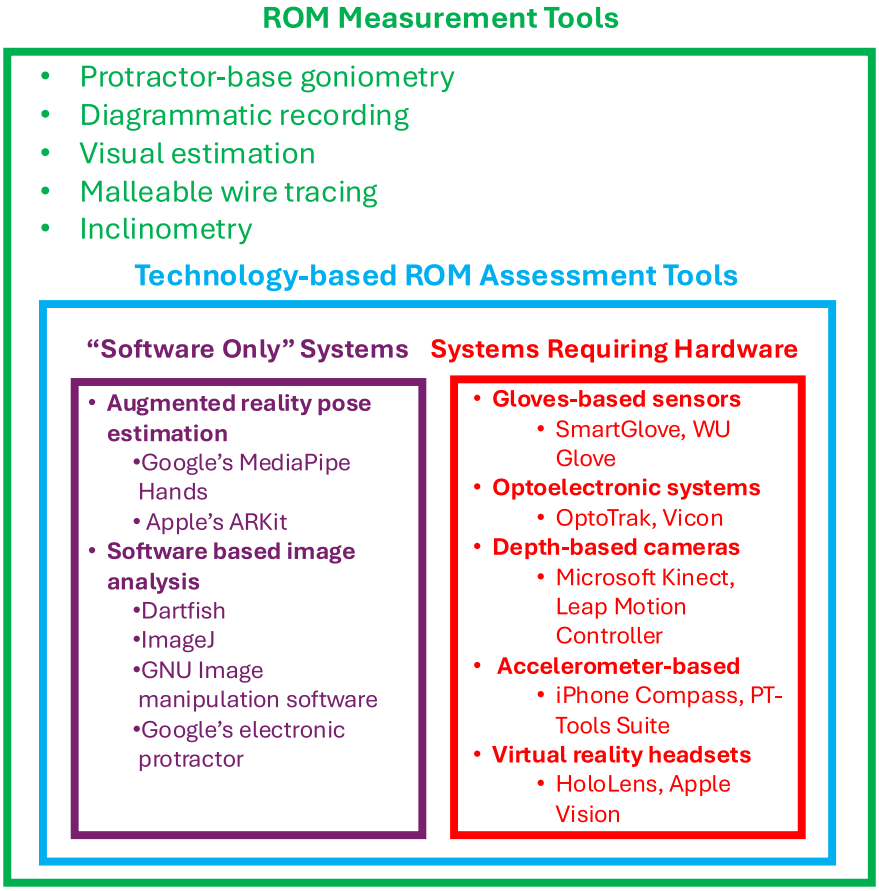

Fig. 1. Classification of ROM measurement techniques and devices. ROM = range of motion.

specific physical device for capture (Fig. 1). Such "hardware-based tools" can range from gloves to virtual reality-based systems, such as Apple Vision Pro or HoloLens. Even accelerometer-based applications, such as iPhone Compass, which have been used to measure finger joint ROM, require mobile devices with internal inclinometer capability.[6,7] Conversely, the term "software only solutions," is used to refer to measurement tools that require only computer or smart device technology with internet capability, such as computer vision-based augmented reality (AR) or image analysis systems (Fig. 1). Compared with hardware-based technology, software-only solutions may represent more practical and accessible solutions for large-scale clinical use both during in-person and virtual care.[8]

Telerehabilitation represents one obvious and important application of "software only" ROM capture systems, hereafter referred to as "software-based" systems. Telerehabilitation refers to "the delivery of rehabilitation services via information and communication technologies," and encompasses services that include assessment, prevention, treatment, education, and counseling.[9] Telerehabilitation can increase accessibility of therapy for rural and remote populations,[10-18] while reducing travel and financial burdens on patients and caregivers, including missed work, and cost of accommodation near tertiary care centers, parking fees, and childcare.[19-21] Both therapists and patients have reported interest in continuing to use telerehabilitation in routine clinical practice beyond the coronavirus (COVID)-19 pandemic.[19,22,23] Furthermore, both groups report enhanced patient comfort when interacting with therapists in their own home environment without the distractions of a busy therapy clinic.[23,24] In order to justify its continued use, telerehabilitation must (1) provide comparable assessments to in-person care; (2) enhance rather than compromise accessibility of care; and (3) provide a sufficiently satisfactory experience to ensure ongoing use. Given ROM is the most commonly performed assessment measure during virtual therapy appointments,[22] software-based ROM analysis systems, particularly those that can ultimately be integrated into telerehabilitation platforms, have a considerable role to play in facilitating telerehabilitation use and adoption.

While software-based ROM analysis systems provide an emerging opportunity for improving the efficiency and effectiveness of in-person and remote care, literature regarding their development and application is frequently siloed within engineering journals. To stimulate therapist buy-in and adoption as well as engagement in the development of such technologies, knowledge translation from the realm of technology development and engineering to clinical practitioners must occur. This review article aims to (1) define the landscape of current software-based ROM analysis systems; (2) discuss considerations and challenges inherent in the development of software-based technologies; and (3) propose future directions for integration of software-based ROM analysis systems into clinical practice.

The current landscape of software-based ROM assessment systems

Software-based ROM analysis systems encompass the technologies that enable ROM measurements to be taken using only computer programs or software. An important distinction of such technologies as compared to those requiring a hardware component is that software-based systems may be used across devices, as long as devices meet specific operating system criteria, such as internet and/or video capability. Current software-based techniques can be largely subclassified into image analysis measurement systems or AR pose-estimation measurement systems (Table 1). These, as well as various other technology-

Table 1
Types of software-based ROM measurement systems in the hand and wrist and their advantages and disadvantages with regard to integration into a clinical practice

	Photography-based with or without additional image analysis	Single-camera AR pose estimation–based hand tracking
Explanation	Analysis of images taken on a smart device or other camera with analysis using a goniometer on the image itself or using specialized analysis software	Software that uses ML to estimate the position of 3D spatial landmarks on the hand using camera feed input and converts them into angle measurements

Example technologies	● Smartphone photography[28]
	● Image analysis software
	  ● DartFish[25]
	  ● ImageJ[26,28]
	  ● GNU Image manipulation software[29]
		Software based on
		● MediaPipe Hands ML framework[34-37,39]
		● ARKit (only for use on iOS devices)

Advantages	● Accessibility of smart device camera capture	● Accessibility of smart device RBG camera use ● Reduced time associated with real-time ROM capture in multiple joints simultaneously ● Reduced cost associated with pretrained open-source ML frameworks ● Only requires storage of hand landmark and ROM data
Disadvantages	● May require patients have assistance for photography ● Potentially time-intensive image analysis on therapy side ● Security risks associated with storage and upload of images to image analysis software	● Relies on patient to position hand relative to camera ● Potentially poor performance in hands with atypical anatomy due to pretraining on healthy hand dataset

ROM = range of motion; AR = augmented reality; ML = machine learning.

based ROM measurement and motion analysis systems, are reviewed individually in a recent scoping review, including their accuracy relative to the reference standard, which is typically manual goniometry.[8] In this section, we aim to present an overview of current software-based systems, including their advantages, limitations, and overall clinical utility, some of which are also laid out in Table 1.

Image analysis systems

Image analysis–based ROM measurement requires users record videos or images of their affected hand or digit and upload them to commercial software programs such as Dartfish, a sports performance analysis software with motion analysis capability for ROM measurement of the wrist,[25] or open-access software programs, such as ImageJ, GNU Image Manipulation Program (GIMP), or Google Chrome electronic protractor.[26-30] These systems allow image capture either by the patient or clinician followed by upload and image analysis, typically, by the clinician. Some software systems, such as Dartfish, have built-in capture systems within their mobile applications.[31] An advantage of such measurement techniques, particularly for telerehabilitation or remote monitoring purposes, is that they allow asynchronous use, meaning patients can capture images of their hand for later analysis by the clinician. A downside, however, of such technology is that measurements are typically dependent on clinician proficiency with the software, as clinicians must select points or lines on the image, which allow the software to then calculate the ROM. For example, using Dartfish, the system measures ROM by tracking specific predefined markers selected within the software.[32] Similarly, other image analysis software systems, such as ImageJ, require the clinician place bisecting lines along the posterior aspects of adjacent phalanges such that the software can generate the resulting joint angle. As such, these software systems provide the convenience of remote monitoring capabilities, which are appealing for telerehabilitation and remote monitoring systems. However, these programs are highly user-dependent, introducing potential user learning curves as well as possible issues with reliability, although numerous studies have demonstrated high intra- and inter-rater reliability across various software options.[25,27,29,30]

Pose estimation and AR-based ROM motion analysis

AR refers to the overlay of computer-generated images or objects onto real-world visual input—either real-time web-cam feed or uploaded videos. In the case of AR-based ROM measurement, computer-generated hand joint landmarks are overlaid onto camera feed of the hand and move in real time as the hand changes position relative to the camera. Google's MediaPipe Hands AR framework is currently the most investigated AR-based hand tracking motion analysis system providing real-time, markerless hand tracking using a single RGB camera, the type of camera found ubiquitously in smart devices.[33-37] However, other AR hand tracking frameworks, including Apple's ARKit hand tracking framework, are under development. As an example, Google's MediaPipe Hands framework uses two complimentary models for hand tracking: (1) a palm detector model that locates the hand in space within a bounding box; and (2) a hand landmark model to locate 21 2.5-dimension hand landmarks within the detected hand.[38] Landmarks are denoted as 2.5-dimensional because they incorporate the two-dimensional x- and y-coordinates derived directly from the hand's position in the two-dimensional image or video input as well as an extrapolated depth-plane z-coordinate generated by a trained machine learning (ML) pose estimation algorithm.[33]

AR-based motion analysis systems can be administered widely without additional physical equipment costs to the patient or healthcare system required for similar hardware-based systems, such as virtual reality headsets or depth-based cameras. Furthermore, unlike image analysis systems, landmark detection and ROM measurement are performed using computer vision and pose estimation, removing the clinician from the measurement process and, thereby, potentially reducing issues related to inter-rater reliability. A recent study looking at the reliability of AR-based measurement using the MediaPipe Hands framework demonstrated excellent inter-trial reliability of the technology.[39] Additionally, because this technology can measure joint ROM in real time as the patient is interacting with the system, AR-based technology has the potential to not only allow asynchronous patient-clinician interaction with the tool, but also provide patients with real-time feedback as they perform exercises independently. This latter is important for telerehabilitation platform considerations, such as gamification of remote therapy tools.

Considerations and challenges in the development of software-based ROM analysis systems for clinical use

The role of open-source solutions

Open-source technology represents an emerging opportunity for platform development within the realm of ROM analysis. Open-source frameworks refer to reusable, publicly available software code, tools, and libraries that application developers can use to build custom applications. Some examples of open-source libraries include the React library written in JavaScript, the Django library written in Python, and Google's

MediaPipe library that comprises a large collection of ML frameworks written in both JavaScript and Python. Meanwhile, open-source software, such as ImageJ, exist as well with community-driven development of code, software extensions and updates all directed toward optimization and extension of the utility of the software. Open-source frameworks and software have the potential to provide a basis for the efficient development of innovative healthcare tools across many areas of medicine, ranging from ROM measurement applications to diagnostic imaging, without the prohibitive time and costs associated with commercial licensing fees and the time associated with development of new software from scratch.[40-42] In the medical field, where funding for research and technology development is scarce and reliant on competitive grants, open-source frameworks present an attractive option for developing clinical tool prototypes based on free, pretrained models. Additionally, through the use of user and developer forums, open-source software has potential to be both more customizable and more responsive to user needs compared with industry-based or commercial vendors.[40,41]

While embracing the open-source community has important advantages for technologic innovation, therapists, developers, and researchers looking to take advantage of open-source solutions should be aware of their potential pitfalls. First, although many open-source libraries are developed with high quality and security standards, the quality and security of such tools varies, and they may possess inherent vulnerabilities by virtue of having publicly available source code.[42] Furthermore, open-source code relies heavily on an invested community of developers, who provide enhancements to the function and security of the frameworks.[40,42] Unlike commercially developed software, there are no guarantees regarding the intent, reliability, or longevity of the communities supporting many open-source frameworks.[42] As a result, although open-source frameworks represent an excellent basis for the development of innovative prototypes for medical applications, careful consideration of the sustainability and quality of such tools should be exercised with regard to sole reliance on these frameworks as the basis for complex medical technologies intended for long-term clinical use, such as software-based measurement tools.

Reliability and concurrent validity

As is the case in the development process for any novel technique or tool for clinical practice, newly developed telerehabilitation systems must demonstrate acceptable reliability and validity relative to the gold standard, typically manual goniometry. Reliability refers to the consistency of successive measurements on the same subject under similar conditions.[43] Meanwhile, concurrent validity is a subset of criterion validity that refers to the degree to which a new measurement technique agrees with the "gold standard," also known as the "criterion."[7,29,34,44,45] Both reliability and concurrent validity provide valuable information about the amount of error therapists can expect with regard to values produced by their measurement technique. As mentioned previously, Kuchtaruk et al provide a review of the reliability and accuracy of numerous software-based ROM measurement tools.[8] Formal peer-reviewed assessment of the reliability and concurrent validity of emerging software-based motion analysis applications can be onerous and time-consuming, particularly when validating ROM analysis tools in patient populations. Additionally, further development of patient- and clinician-facing platforms for integration into telerehabilitation tools requires an iterative design process based on findings of interim validation studies as well as feedback from the ultimate users of such tools, including clinicians and patients.[46,47]

Accessibility

Virtual small joint ROM analysis must balance maximization of accessibility without compromising utility or quality of the clinical data collected. For example, although software-based tools bypass costs associated with hardware-based ROM measurement tools, sophisticated, validated proprietary software, such as DartFish, still incur accessibility limitations associated with purchase of software licenses.[31] The process of not only developing, but also integrating image analysis or computer vision technology into patient- and clinician-facing platforms or telerehabilitation tools, is time-consuming and costly. Therefore, as such applications become increasingly validated and commercialized, user fees for patients, clinicians, or institutions may limit their accessibility.

Several studies have demonstrated that a vast majority of patients not only have access to smart devices and internet, but also feel comfortable using these devices.[48,49] However, even with the ubiquity of smart devices, differing degrees of technology literacy among both clinicians and patients may post barriers to use and integration of such software into clinical practice, be it in-person or virtually. From the patient perspective, developers should consider relationships with technology across age and educational levels. Tool design should be targeted at patients across a spectrum of ages, including pediatric, adult, and elderly patients, while still ensuring the output is useful for therapists and clinicians. For example, gamification of rehabilitation may be of greater interest to younger populations, while older patients may be more likely to benefit from simpler goal-directed therapy or even simply comparison to their unaffected side.[50] Further, the advantage of software-based motion analysis over systems requiring separate hardware is that it allows patients and clinicians to use their own devices, reducing the burden and anxiety associated with learning new technology or purchasing additional hardware.[51,52] Indeed, for clinicians already using smart devices in routine in-person practice to, for instance, upload photos of wounds to the electronic record or provide videoconference-based telerehabilitation visits, software-based motion analysis systems may also be more easily utilized as an adjunct to in-person clinical practice compared with hardware-based ROM measurement technology requiring use of additional devices.

Finally, an essential aspect of accessibility when using image analysis and computer vision technology is ensuring the technology is able to perform across different anatomy and skin tones. This is particularly relevant when considering motion analysis systems, such as Dartfish, that employ marker color for hand tracking.[32] Additionally, ensuring ML computer vision frameworks are trained using a repository of images with diverse skin tones is essential. For example, Google's open-source MediaPipe Hands model has been trained on over 10,000 real-world images with varying backgrounds and hand gestures as well as over 100,000 synthetic hand model video sequences with varying skin tones and textures.[33] However, such pose estimation models are typically trained on hands with normal anatomy, resulting in potential difficulty tracking hands with atypical anatomy or postures, such as amputations or severe contractures.[35]

Patient-driven ROM capture

With software-based motion analysis, particularly with regard to their application to telerehabilitation settings, the onus of data capture is shifted from the clinician to the patient. Although accessibility and validity of applications are key parameters in facilitating capture of quality motion data, systems that perform poorly across different backgrounds, lighting, and hand positioning relative to the capture tool will be less likely to yield useful results in clinical practice. The patient environment, device position, and hand poses required for accurate data acquisition should be considered early in the development process.[36] In turn, applications that are more robust and can perform consistently despite high degrees of variation in the data collection environment will be easier for patients to use and are more likely to yield useful data.

Regulatory body approval

Finally, in addition to acquiring both therapist and patient buy-in, novel software-based finger motion analysis systems developed for widespread patient and/or therapist use will require regulatory approval.[53] In the United States, for example, most telerehabilitation or software-based measurement tools are considered class II devices by the Food and Drug Administration if they are used to inform decision-making by the care provider.[54,55] Such devices must have evidence of demonstrated safety and effectiveness as well as the ability to prove they are sufficiently similar to other products already on the market.

Furthermore, prior to integration into clinical practice, these tools must be compliant with the privacy standards of regional regulatory bodies. Potential privacy concerns should be considered throughout the development process, including in the selection of patient-therapist image sharing and storage of any data in such applications. AR-based measurement represents an opportunity to reduce privacy concerns, as ROM measurements are collected using spatial landmark data from camera feed without the need to store image or video data. By comparison, image analysis systems, such as Dartfish, or photography-based ROM measurement techniques may be more likely to raise privacy concerns due to the need to receive, upload, and/or store images.[31]

Future directions of software-based ROM analysis systems in clinical practice

Clinician and patient needs and desires

Literature eliciting clinicians' and patients' needs regarding software-based ROM motion analysis systems and even telerehabilitation platforms is lacking and represents an important future area of study. However, several important conclusions may be drawn from the satisfaction literature regarding the use of telerehabilitation and virtual care. First, there is high degree of satisfaction among both therapists and patients with virtual care, with a majority expressing interest in future use of telerehabilitation.[19,20,22,56] Indeed, therapists using telerehabilitation during the COVID-19 pandemic reported remote visits motivated patients to assume greater responsibility for their own recovery and integrate exercises into their daily activities.[24,57] They also noted that seeing gains throughout therapy increases patient motivation to continue with prescribed exercises.[24] Thus, given ROM is the most commonly measured parameter of hand recovery via telerehabilitation visits, there is impetus for development of high-fidelity software-based ROM analysis systems that can be integrated into telerehabilitation platforms. Additionally, a commonly identified need in the telerehabilitation literature is the capacity for synchronous and asynchronous patient-therapist interaction within the platform.[46,53] As such, AR-based motion analysis, in particular, represents an ideal system for integration into telerehabilitation platforms, as its ability to perform measurements in real time without clinician involvement allows it to be used both synchronously during telerehabilitation visits and asynchronously by patients who want to track their progress during prescribed exercises or gamified therapy.[53]

Finally, both therapists and patients identify ease of use of the chosen platform to be an important facilitator of ongoing use. Ivy et al identified an association between therapist age and utilization of telerehabilitation.[58] From the patient perspective, patients also desire systems that are simple to use and which can be relied upon to work consistently.[19] Meanwhile, other studies have indicated the technological difficulties are a barrier to current and planned future use of telerehabilitation platforms.[59] Although not specifically applied to software-based motion analysis systems, the inference that can be drawn from these studies is that ease of use of technology predicts continued and future use.[50] As a result, software-based ROM systems should be intuitive with easy access to instructions for use or even technologic support. As such, we envision within the AR-based measurement systems, for example, development of automated prompts to cue patients on how to improve measurements, such as improving lighting or changing hand position or distance from the camera.

Integration of ML and artificial intelligence (AI)

There are many potential applications of ML and AI in the realm of software-based motion analysis within both AR-based and image analysis–based hand tracking. Because AR-based measurement eliminates reliance on the clinician to identify landmarks, this system has the capacity to benefit from updated ML models and AI for continued improvement. For example, we envision future AR-based motion analysis systems will have integrated ML models that can be continuously trained with clinician or patient feedback regarding the accuracy of landmark placement. Additionally, although not specifically within the field of hand tracking, pretrained ML plug-ins and libraries are actively being developed for open-source image analysis software, such as ImageJ, in order to enable object and pattern recognition.[40] ML-mediated marker identification could help reduce the reliance of image analysis on clinicians, increasing efficiency of such tools, while reducing inter-observer variability.

Furthermore, AI represents, as yet, one largely untapped opportunity to optimize the efficiency and utilization of scarce subspecialist hand therapy resources. AI could be used to recognize trends in ROM measurements over time, flagging patients who are failing to progress with home therapy exercises or in need of earlier intervention. Additionally, appropriately trained AI models could potentially provide therapist- approved recommendations or precautions based on patients' ROM motion analysis. For example, patients progressing too rapidly in a therapy program, such as a flexor tendon rehabilitation protocol, could receive a warning recommending the patient reduce their arc of motion or contact their therapist for help

Use in the in-person setting

Although their applications in the setting of telerehabilitation may be more evident, software-based motion analysis systems may be a valuable tool in the in-person clinic setting. For example, although most hand therapists are highly proficient with manual goniometry, AR-based ROM tools have the ability to simultaneously measure all joints in the hand in real time within seconds,[36] allowing therapists to rapidly and efficiently measure ROM in the affected and unaffected hand. Additionally, software-based systems have a role in settings where physically applying a goniometer to the hand is an issue. For example, taking a photo of a hand with significant wounds, as in the setting of burn care, may be both less painful and more hygienic than using manual goniometry. Furthermore, in the setting of pediatrics where watching patients at play is often easier than providing specific commands, using image analysis or AR-based ROM measurement may provide more accurate measurements of active ROM. Thus, as the reliability and accuracy of software-based motion analysis systems continues to improve, there is increasing impetus for these to be used in clinical settings.

Conclusions

In conclusion, software-based motion analysis systems represent a highly accessible solution with applications for both virtual and in-person care. While ongoing development of such systems is needed to ensure their clinical validity and to optimize the clinician and patient experience during use, these applications have a role in

improving the efficiency and quality of care for certain populations, such as those living remotely, patients with significant wounds, and pediatrics. Additionally, through reduction of clinician dependency for measurement, AR-based systems may provide patients with real-time feedback, empowering them to become more engaged in their care.

Author contributions

Sasha Létourneau: Writing – review & editing, Writing – original draft, Conceptualization. **Caitlin Symonette**: Writing – review & editing, Writing – original draft, Conceptualization.

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JHT Read for Credit

Quiz: # B46

Record your answers on the Return Answer Form found on the tear-out coupon at the back of this issue. There is only one best answer for each question.

#1. The study sought to
   a. propose future directions for utilization of software-based ROM analysis
   b. define the landscape of current software-based ROM analysis
   c. present challenges in the development of software-based technologies
   d. all of the above

#2. To date _____ in the use of software-based systems in the analysis of ROM
   a. only intra rater reliability has been established
   b. only interrater reliability has been established
   c. validity and reliability have not been established
   d. only concurrent validity has been established

#3. Future development will likely incorporate
   a. AI applications
   b. Zoom technology
   c. patient interviews
   d. chart reviews

#4. “software only solutions” require
   a. gloves fitted with joint sensors
   b. only computer technology
   c. AI elements
   d. Zoom technology

#5. Hopefully the new technologies will enhance patients’ involvement in their own care
   a. not true
   b. true