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THE USE OF TECHNOLOGY IN ORTHOPAEDIC SURGERY—INTRAOPERATIVE AND POST-OPERATIVE MANAGEMENT (C KRUEGER AND S BINI, SECTION EDITORS)

How New Technology Is Improving Physical Therapy

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Abstract

Purpose of Review As rehabilitation patient volume across the age spectrum increases and reimbursement rates decrease, clinicians are forced to produce favorable outcomes with limited resources and time. The purpose of this review is to highlight new technologies being utilized to improve standardization and outcomes for patients rehabilitating orthopedic injuries ranging from sports medicine to trauma to joint arthroplasty.

Recent Findings A proliferation of new technologies in rehabilitation has recently occurred with the hope of improved outcomes, better patient compliance and safety, and return to athletic performance. These include technologies applied directly to the patient such as exoskeletons and instrumented insoles to extrinsic applications such as biofeedback and personalized reference charts. Well-structured randomized trials are ongoing centered around the efficacy and safety of these new technologies to help guide clinical necessity and appropriate application.

Summary We present a range of new technologies that may assist a diverse population of orthopedic conditions. Many of these interventions are already supported by level 1 evidence and appear safe and feasible for most clinical settings.

Keywords Blood flow restriction · Exoskeleton · Biofeedback · Instrumented insoles · Patient-centered care · Musculoskeletal ultrasound

Introduction

The steady increase in the burden of musculoskeletal injury conditions in the USA has brought focus on the high rates of disability, chronic pain, and reduced quality of life when patient outcomes are below optimal [1]. The overall aging of the population and longer life expectancy will drive more patients to seek medical care to improve age-related musculoskeletal decline and injury. This burden is not isolated to the aging population, but across the lifespan of individuals who suffer high and low energy orthopedic trauma from sports, work, combat, and everyday life.

Through advancements in technology, post-injury rehabilitation is leveraging the ability to push the envelope in hopes of an expedited recovery, standardization of treatments, closer discharge to prior injury status, and reduced disability. The aim of this paper is to highlight new technology currently being used in Physical Therapy for orthopedic conditions ranging from sports medicine to joint arthroplasty to trauma.

Blood Flow Restriction Rehabilitation

During the quiescent period of recovery from injury or surgery, patients are susceptible to rapid and significant losses in muscle strength and size [2, 3]. Current guidelines

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recommend lifting moderate to heavy resistance exercise loads, 65–70% 1 repetition maximum (1RM) to create a physiological response for muscle adaptation and slow the loss of muscle during periods of disuse [4]. Often, post-operative restrictions and pain curb the clinical population's ability to handle these recommended loads. This creates a paradox for rehabilitation professionals who try to limit disuse atrophy and restore muscle quantity and quality when constrained to low-loads. Blood flow restriction (BFR) rehabilitation has recently gained in popularity in the clinical setting via the ability to achieve similar benefits as high load training while using loads below 30% 1RM.

The application of BFR requires applying a tourniquet cuff, similar to a surgical tourniquet, to the proximal thigh or arm to reduce arterial inflow while completely occluding venous return (Fig. 1). By combining BFR with low-load exercises increases in muscle size and strength similar to heavy-load training have been demonstrated [5••, 6]. Although BFR is low-load, it is high volume with most exercise prescriptions requiring 75 repetitions. Current guidelines suggest personalization of the cuff pressure to each individual may help prevent injury and improve standardization and efficacy of treatments [7•]. This personalization is often termed limb occlusion pressure (LOP) or arterial occlusion pressure (AOP) in the current literature. Personalization is achieved through BFR systems with built-in doppler like technology or via hand-held doppler measurements [8, 9]. Although the amount of restriction pressure needed to maximize effectiveness and safety is still under investigation, recent research suggests that in the lower extremity 60% limb occlusion pressure may be the minimum effective dose to achieve a response with pressure up to 80% possibly augmenting the response [10]. As the ability to tolerate load decreases, then the applied occlusion pressure may need to increase. This may be important in clinical settings where patients may not tolerate even 20% of 1RM; in this case, up to 80% LOP in the lower extremities may be required to reach similar adaptations as heavy-load training [11].

Fig. 1 Patient performing blood flow restriction rehabilitation

Systematic reviews and meta-analysis have demonstrated the effectiveness of BFR in healthy, clinical, and elderly populations [7•, 12, 13]. Although the exact mechanisms behind BFR and muscle adaptation are still not fully understood, several theories have been presented. One prevailing hypothesis is the recruitment of larger, fast-twitch motor units during the hypoxic state created by the tourniquet. This, in turn, creates a muscle metabolite milieu that signals downstream anabolic signaling including increases in muscle protein synthesis, myonuclei, growth hormone, and muscle and bone gene expression [14–16].

Although relatively new and novel in the clinical setting, the overall safety of blood flow restriction has been studied in both healthy and clinical populations with minimal side-effects [17]. The majority of published and ongoing clinical trials have focused on sports medicine injuries; however, total joint, limb salvage, and muscle wasting disease populations have been studied without adverse events and with positive results [18–20]. Although BFR research has focused primarily on muscle adaptations, recent studies have demonstrated the ability of BFR to improve tendon stiffness and tendon cross-sectional area similar to heavy-load training and reducing bone loss after ACL surgery [21, 22•]. Ongoing and future trials will help identify which diagnoses are the most appropriate for BFR and establish best practice guidelines for early use of BFR, LOP, and dosing protocols post-surgery to maximize the response. Since the majority of orthopedic patients experience periods of disuse from injury or surgery, BFR appears to be a promising new technique to mitigate the loss of muscle that has historically been an accepted consequence of injury.

Exoskeletons for High Energy Lower Extremity Trauma

The decision to amputate or salvage a limb after high energy lower extremity trauma (HELET) remains controversial. Factors such as patient-perceived expectations, surgeon preference, and conflicting published trials have made consistent guidelines difficult to establish. Although the LEAP study found no difference in functional outcomes at 2 and 7 years between open-tibia fractures who went on to limb salvage or amputation, a subsequent military study, METALS, reported overall improved functional outcomes in service members who elected amputation over limb salvage [23, 24]. The disparity in the results of these studies may be in large part due to the higher physical fitness and functional expectations in the younger and more active military population. In turn, this could lead to a loss of self-efficacy in the limb salvage military cohort from the inability to perform military tasks such as running.

With increasing numbers of service members undergoing limb salvage during Operation Iraqi and Enduring Freedom, more robust and aggressive rehabilitation programs began to develop to accommodate the prolonged circular ring fixation phase [25]. Unfortunately, the loss of plantarflexion force and pain that persisted despite bone union left the majority of the limb salvage patients unable to stay on active duty [26]. To combat this, a custom energy-storing carbon fiber ankle-foot orthosis called the intrepid dynamic exoskeletal orthosis (IDEO) was developed. The IDEO utilizes a foot-plate with a rollover design to allow engagement from heel strike to toe-off to load posterior struts that simulate plantarflexion torque (Fig. 2). Additionally, minimal ankle and foot range of motion is allowed in the IDEO which helps reduce pain from sources like post-traumatic osteoarthritis. This allows individuals to tolerate high impact activities and if higher-level tasks such as running are desired then applying more force through the mid-foot of the device increases the strut loading with a subsequent increase in power [27, 28]. To aid service members in the utilization and optimization of higher-level function in the IDEO, a specialized rehabilitation program called the Return to Run (RTR) Clinical Pathway has been developed [29]. The combination of IDEO and RTR has led to reduced delayed amputation rates, improved self-reported scores, improved validated performance outcomes, and improved return-to-duty-rates. Furthermore, the results appear translatable across multiple military institutions [30••]. Although overall adoption outside the military setting has been slow, partly due to reimbursement rates, there has been a recent rise in civilian medical centers and prosthetic companies adopting an exoskeleton type device coupled with aggressive rehabilitation.

Fig. 2 Intrepid dynamic exoskeletal orthosis (IDEO)

Force Plates

Force plates measure force production over time, providing insight into the kinetics of functional movement. Force plate manufacturers have produced affordable hardware and clinician-friendly software solutions that analyze and report kinetic performance with dual plates in real-time. We use functional testing batteries with bilateral comparison of kinetic performance in the clinical setting. These protocols take only a few minutes and can be analyzed without the assistance of a biomechanist. Applications include baseline kinetic profiling, a monitoring tool and outcome measure during rehabilitation, and to assess athletes' response to training.

Dual force plates can assess each limb's ground-based movements or can be used individually for single-leg movements. The most studied test batteries include the squat jump, counter-movement jump, and mid-thigh high pull [31–33]. These provide reproducible performance metrics well suited for profiling and monitoring purposes [34••].

The force-time curve is compared with the kinematics of the athlete to quantify force application during specific phases of the movement (see Fig. 3). Phase specific metrics are used to profile performance kinetics. During rehabilitation, deficits in kinetic performance are identified via a comparison of force during bilateral tasks [35, 36]. Video or motion capture synchronization allows the clinician to determine if deficits are specific to contraction type or joint position. These deficits are targeted in rehabilitation or training plans and monitored as outcome measures.

Our understanding of the relationship between dual force plate performance and musculoskeletal health is rapidly evolving. Asymmetry in force production appears to be a risk factor for subsequent injury in some sport populations [37]. However, asymmetries are likely task-specific and may be normal in sports that are not bilateral in nature [38••]. There is a growing body of literature describing normative symmetry in specific sport populations that can be used to guide clinical decisions [38••]. As force plates are used more broadly in clinical and research settings, we expect to learn how an individual's force profile affects their future musculoskeletal injury risk and ability to perform in sport.

Motion Capture and Video Biofeedback

Video motion capture tools are now freely available to the general public. Smartphone-based applications leverage high speed video and machine learning algorithms to create biomechanical models that can be used in real time. The size and price of IMU sensors, comprised of accelerometers, gyroscopes, and even GPS, now allows for accurate 3-dimensional motion capture to be performed in the clinic or on the field. Early clinical use of this technology was limited to periodic screening of standardized movements. However,

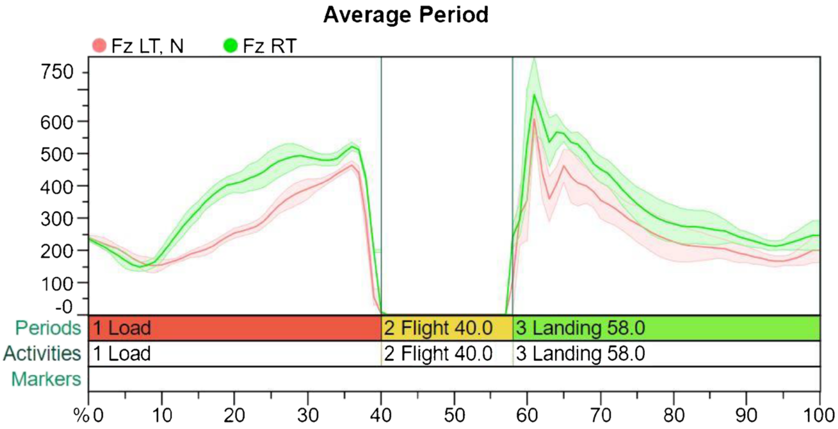


Fig. 3 Force-time curve obtained from dual force plates during a counter-movement jump reveals asymmetry in force production during the propulsion phase of the jump

we are now able to use these technologies to quantify and visualize real-time movement during rehabilitation exercises. By involving the patient in this live analysis of their movement, this technology can be used as biofeedback.

Real-time video or motion capture biofeedback increases a patient's awareness of their movement signature. Patients can interact with live motion capture displays to modify or correct their movement based on clinician cues. We have found that displaying graphical summaries of movement, such as bar charts for range of motion, provide patients with simple targets to achieve during rehabilitation exercises (see Fig. 4). For example, we may instrument a patient with IMU's and show them a monitor with graphs of bilateral knee extension during treadmill walking. Instead of providing internal cues, the therapist asks the patient to strive for symmetry of the injured and non-injured knee from the graphical display. Early research on biofeedback shows greater effects in motor learning than conventional physical therapy [39].

Musculoskeletal Ultrasound in Soft Tissue Injury

Ultrasound is an ideal musculoskeletal imaging modality in the outpatient setting due to its high resolution, non-invasive nature, low cost, and ready availability [40]. Traditionally considered a diagnostic tool, advances in technology have led to new applications with potential to guide loading prescription during rehabilitation of soft tissue injuries [41]. We can now visualize soft tissue healing, quantify muscle architecture, and evaluate changes in muscle stiffness and density. These innovations are changing the way we understand muscle recovery from injury—an important development that will improve clinical decision making.

Ultrasound can visualize the location and severity of soft tissue lesions (see Fig. 5). Because ultrasound is low-cost modality and does not use ionizing radiation, it can be used as a periodic assessment tool. The phases of soft tissue healing

Fig. 4 Gait biofeedback

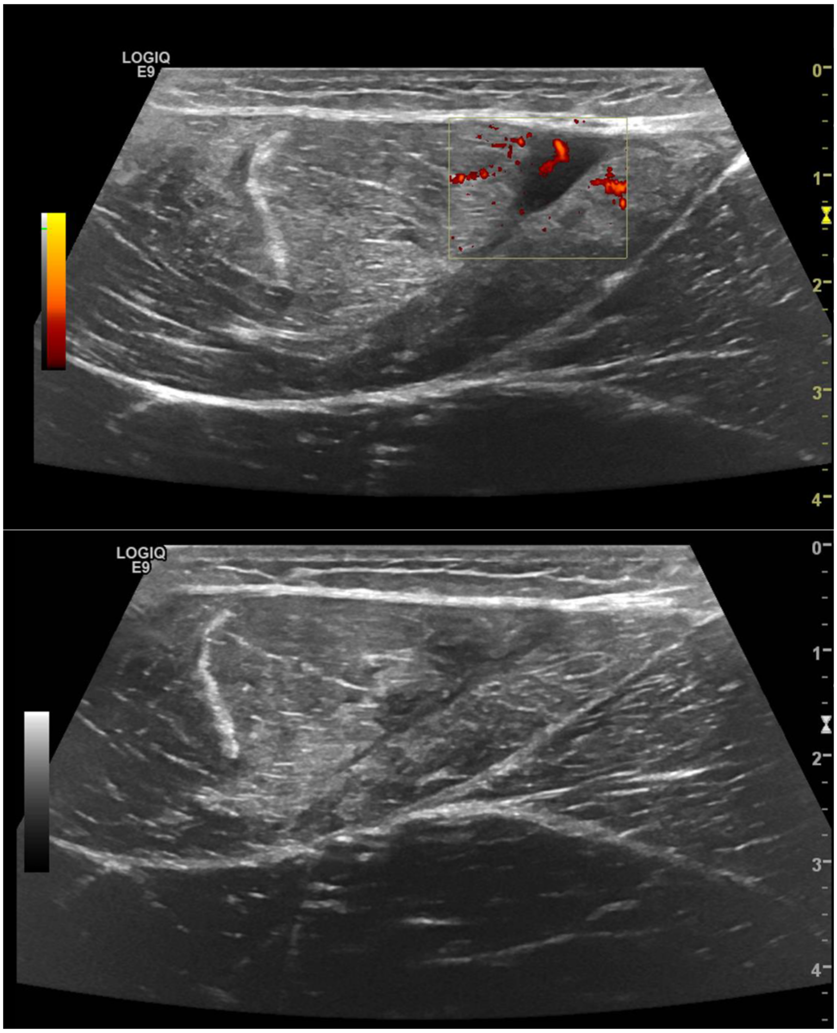


Fig. 5 High frequency ultrasound of rectus femoris showing injury at 2 weeks (top) and healing 6 weeks (bottom) after a myofascial strain of the rectus femoris. From: Aubry S, Nueffer J-P, Tanter M, et al. Viscoelasticity in Achilles tendonopathy: quantitative assessment by using real-time shear-wave elastography. *Radiology* 2014; 274:821–829

can be monitored and classified, including changes in anatomy and vascular activity around the injury. Although still experimental, there are ultrasound criteria-based protocols guiding return to activity after injury that are being tested in sports medicine settings [41].

A muscle's capacity to create and absorb force largely depends on its architecture. Muscle architecture is defined by shape, thickness, fascicle length, and pennation angle [42]. By assessing these characteristics, we can determine if a muscle's morphology is appropriate for the mechanical demands placed on it during sport with reliable validity [43]. For example, shorter biceps femoris long head fascicle length is associated with increased risk of hamstring strain. This is a modifiable risk factor that can be changed with just a few weeks of eccentric exercise [44]. These findings suggest that there is a role for ultrasound as a screening and monitoring tool for patients at risk of muscle strain.

Ultrasound technology has been developed that allows the clinician to quantify the elasticity and functional recovery of a tissue [45]. This application spawns from cancer research, where density can be used to differentiate abnormal soft tissues masses from surrounding normal anatomy. In musculoskeletal medicine, these techniques could be used to provide valuable information on tissue health and load-bearing capacity, such as identifying stiffness in shoulder capsules in overhead throwers, or loss of stiffness in Achilles tendinopathy [46, 47]. As this technology evolves, we expect it to have a place in the outpatient clinical setting as a diagnostic and load management decision-making tool.

Instrumented Insoles: Use of Real-time Feedback to Improve Patient Outcomes

Recent advances in instrumented insoles have enabled clinicians and researchers to access kinetic and spatiotemporal data formerly confined to biomechanical laboratories in the clinical or free-living environment. Instrumented insoles such as the Novel Loadsol (Novel.de) are available at low cost, capable of providing data in real-time to an Android or iOS device, and can provide numerous forms of biofeedback (haptic, auditory, and visual) to users. This technology has been utilized to improve movement quality, increase lower limb loading, improve adherence to weight-bearing restrictions, and beneficially alter gait mechanics.

Compensatory movement patterns are common following lower extremity orthopedic surgeries. Multiple studies have noted persistent compensatory movement patterns for years following unilateral total knee arthroplasty (TKA) during functional tasks including sit to stand, gait, and stair navigation [48–53].

These compensatory movement patterns are characterized by disuse of the surgical limb, resulting in smaller knee extension moments which contribute to persistent quadriceps weakness and poor physical function [54–56]. Additionally, the greatest predictor of movement compensations 1 month following unilateral TKA was the presence of compensations preoperatively [55]. Collectively, these findings suggest that compensatory motor patterns are learned prior to surgery and do not respond to impairment-based rehabilitation. In addition, compensatory movement patterns may be linked to progression of knee osteoarthritis (OA) and subsequent TKA in the non-surgical limb due to increased loading on the non-surgical knee. Therefore, there is a need for improved post-operative rehabilitation using motor learning principles, which may be combined with instrumented insoles.

Retraining compensatory movement patterns requires successful motor learning. Successful motor learning requires frequent and random practice which is not feasible in many clinical settings [57]. While biofeedback has been used in laboratory and rehabilitation settings to improve movement quality, these interventions have been limited due to low practice volume and feedback during a small number of tasks in a highly controlled environment [58, 59•, 60]. Instrumented insoles provide a means of assessing movement quality during a variety of activities occurring in real life environments using varying feedback schedules for optimal motor learning. The authors (MR, MB) are currently conducting a randomized controlled trial (NCT03325062) using instrumented insoles to provide real-time feedback in combination with motor learning principles to improve movement quality following unilateral TKA. Pilot data informing this study showed that this intervention improved movement quality during functional tasks 6 months post-operatively [61].

Instrumented insoles have also been used to facilitate improved limb loading in the early post-operative period as well as improved adherence to weight-bearing restrictions. In a non-randomized trial by Raaben et al., individuals without weight-bearing restrictions following lower extremity surgery were trained to increase loading of their involved limb during gait [62]. They showed improvements to 63% weight-bearing when receiving real-time feedback. This same group of researchers is expanding their work to a multicenter randomized controlled trial involving elderly individuals following proximal femoral fracture [63]. Conversely, weight-bearing restrictions are common following surgery, and most individuals, especially older adults, are unable to maintain weight-bearing restrictions [64, 65]. In order to improve adherence, instrumented insoles have been used to provide real-time feedback to train correct weight-bearing resulting in short-term success but limited carry-over at longer-term follow-up [63, 66, 67]. Future studies need to consider how to improve sustainability of training to facilitate learning. Both applications have potential to improve patient outcomes and inform post-operative protocols.

Finally, instrumented insoles have also been used to retrain maladaptive gait patterns. For example, increased lateral pressure of the foot during stance increases knee adduction moments (KAM) which have been positively correlated with severity and progression of knee OA [68, 69]. Three feasibility studies have examined the use of insoles with audio and haptic real-time feedback to alter foot mechanics by medializing plantar pressure [70, 71•, 72]. In these studies, individuals were successful in achieving short-term changes in gait parameters resulting in reduced KAM. These techniques have yet to be used in larger scale randomized trials or with individuals experiencing lower extremity pathology.

Future research utilizing instrumented insoles will most likely expand into additional orthopedic populations that typically demonstrate compensatory movement patterns, such as after lower limb amputation, or those that require specific weight-bearing protocols, such as after lower extremity fracture, to help improve outcomes in these populations. These technologies may also improve remote monitoring which has implications for improving physical activity, recognizing function decline earlier, and tracking falls.

Patient-centered Care in Total Joint Arthroplasty: Tools for Personalized Care Before and After Surgery

Increasingly, patient-centered care is gaining traction in medicine due to its association with improved health outcomes, patient satisfaction, and reduced healthcare costs [73, 74]. The exchange of information between patient and provider is a key component of patient-centered care [75]. Particularly within the field of elective orthopedic surgery, this exchange is particularly important to ensure that decisions align with the patient's preferences, needs, and values [76]. Recent survey data suggests that patients considering TKA desire information regarding their projected outcome after surgery [77–79]. Despite the fact that total joint arthroplasty (TJA) is widely considered an effective surgery, it can be challenging to accurately predict outcomes and recovery for individuals within such a heterogeneous population [80]. Therefore, there is a growing need for the creation of patient-specific information regarding outcomes and recovery in the field of TJA and other elective orthopedic surgeries.

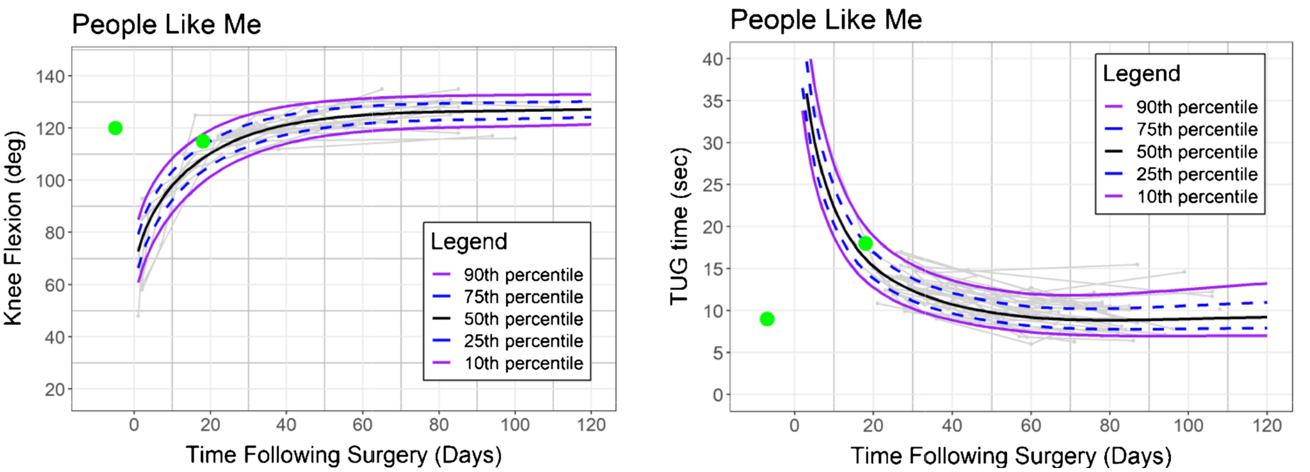
Within the field of TJA, several tools have been developed for use before surgery to help clinicians provide more patient-specific care by utilizing patient-reported outcome measures (PROMs). The Arthroplasty Candidacy Help Engine (ACHE) tool utilizes regression modeling with common PROMs to determine a patient's likelihood of having a successful outcome after TJA [81]. Similarly, utilized logistic regression modeling can create predictive algorithms for PROMs and the likelihood of residual symptoms during common functional activities after TKA [82]. Despite the fact that PROMs are validated measures of recovery, it is important to acknowledge their potential limitations for monitoring recovery after surgery [83]. PROMs may fail to capture a patient's initial functional decline after surgery and have associated more strongly with pain than objective measures of functional performance in TJA recovery [84–87]. It has also been suggested that PROMs are not sensitive to the risk of adverse events, which could allow risks for arthrofibrosis or infection to go undetected [88].

In contrast to the recent increase in tools for personalized care before TJA, clinicians have few tools available to provide patients with individualized recovery monitoring. Existing tools such as the Risk Assessment and Predictor Tool (RAPT) and others have been validated to predict discharge location after TJA [89, 90]. However, there are currently no tools available to our knowledge that allow clinicians to accurately monitor recovery throughout rehabilitation at the level of the individual patient. This is particularly problematic as patients have identified lack of information regarding their course of recovery as a source of anxiety and potential barrier to the decision to undertake surgery [91, 92]. Some patients recovering from TKA have also reported the information they receive about post-operative recovery is either insufficient or incongruent with their actual experience [93].

Personalized Reference Charts: a Novel Tool for Personalized Care

Recently, a "people-like-me" approach has been suggested as a promising new mechanism for providing patient-specific medical care [94]. This approach matches individual patients with similar patients from historical data and utilizes the recovery data from these historical patients to create a personalized estimate of the recovery trajectory for the individual [95]. This "people-like-me" methodology has been proposed as a useful tool for informing patient expectations and post-operative monitoring in patients recovering from orthopedic surgery [96••]. Personalized reference charts (PRCs) are created using "curve matching" which has been utilized to improve the predictive capability of pediatric growth charts [95]. Just as growth charts can be used to predict and monitor an infant's growth based on the historical data of similar children, PRCs can be used to predict and monitor patient outcomes based on the recovery data of previous similar patients.

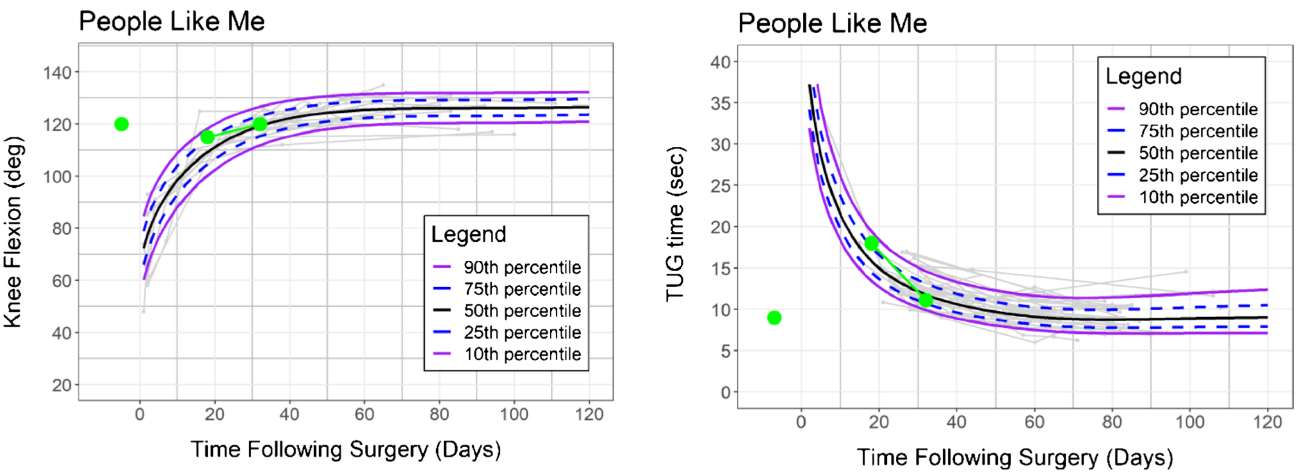
Preliminary work has consisted of creating PRCs for outcome measures which are meaningful in TKA recovery and commonly collected in clinical practice. Knee range of motion (ROM) and timed up and go (TUG) provide a readily apparent example of how PRCs can inform patient-centered care. Consider a hypothetical patient who presents to physical



At 18 days post surgery, the patient's knee flexion ROM is greater than 82% of similar patients

At 18 days post surgery, the patient's TUG time is slower than 75% of similar patients

Fig. 6 PRCs for patient at 18 days after TKA. Values below zero on the x-axis indicate preoperative measures. At 18 days post-surgery, the patient's knee flexion ROM is greater than 82% of similar patients. At 18 days post-surgery, the patient's TUG time is slower than 75% of similar patients



People Like Me

At 32 days post-surgery, the patient’s knee flexion ROM is greater than 55% of similar patients

People Like Me

At 32 days post-surgery, the patient’s TUG time is faster than 70% of similar patients

Fig. 7 PRCs demonstrating a follow up visit 14 days later. The patient’s flexion ROM is still above the median while her TUG time has improved significantly compared to similar patients with TKA. At 32 days post-surgery, the patient’s knee flexion ROM is greater than 55% of similar patients. At 32 days post-surgery, the patient’s TUG time is faster than 70% of similar patients

therapy shortly after TKA. She is anxious about her recovery and unsure if she is on track for a successful outcome. Her physical therapist could utilize PRCs at her initial evaluation to compare her current status to her predicted status at this point in her recovery. In this example, she currently has knee flexion ROM greater than 82% of “people-like-her” and is predicted with substantial certainty to attain a functional level of motion. However, her TUG time, which is a validated measure for monitoring physical function in TJA, is slower than 75% of her peers [97] (Fig. 6).This information could allow her to create a plan of care with her physical therapist that is specific to her individual needs and emphasizes strength and balance (to improve TUG performance) over knee ROM. Additionally, these PRCs could be used to monitor the effectiveness of her plan of care. If she returns to physical therapy several weeks later and demonstrates both a TUG time and knee ROM superior to the median in her PRCs, it provides her the necessary information and the opportunity to discuss the possibility of reduced frequency of care or discharge with her physical therapist (Fig. 7). PRCs could also be used by the surgical team as a screening tool for referral to physical therapy or to determine when additional intervention may be required for a successful recovery (e.g., manipulation under anesthesia). Conceivably, all of these strategies provide the opportunity for improved cost-effectiveness in care after TKA.

PRCs with a “people-like-me” approach has the potential to improve patient-centered care, increase efficiency of care, and facilitate superior outcomes for patients recovering from TKA. Our early work suggests that PRCs are precise and accurate, but the strategy for successful implementation into clinical practice is ongoing.

Conclusion

We live in an age of rapid technology advancements and it is expected that a flood of new technologies will be introduced within the rehabilitation space. To justify the associated monetary cost of new technologies, clinicians will need to turn to well-structured randomized clinical trials to determine the need to adopt. Fortunately, the technologies in this manuscript have already shown promise in published trials or have well-structured trials ongoing. This may serve as a template for other new technologies to avoid the lure of marketing noise and rely more on evidence-based claims.

Compliance with Ethical Standards

Conflict of Interest Michelle Rauzi, Andrew Kittleson, Michael Bade, Julia Johnson, and Dustin Nabhan declare no conflict of interest. Johnny Owens is a paid research consultant for the Major Extremity Trauma Research Consortium and receives royalties from Delfi Medical Innovations, INC.

Human and Animal Rights All reported studies/experiments with human or animal subjects performed by the authors have been previously published and complied with all applicable ethical standards (including the Helsinki declaration and its amendments, institutional/national research committee standards, and international/national/institutional guidelines).

Informed Consent Informed consent was obtained from all individual participants included in the study. Additional informed consent was obtained from all individual participants for whom identifying information is included in this article.

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