Technological Advances in Stroke Rehabilitation

Robotics and Virtual Reality

Deepthi Rajashekar, PhD[a], Alexa Boyer, MASc[a,b],
Kelly A. Larkin-Kaiser, PhD[a,c,d],
Sean P. Dukelow, PhD, MD, FRCPC[a,c,e,*]

KEYWORDS

• Stroke • Robotics • Rehabilitation • VR • Physical therapy

KEY POINTS

- Robotics and virtual reality (VR) are widely studied in stroke rehabilitation to facilitate intensive, repetitive, and engaging therapies.
- Currently, there are some discrepancies between the findings of meta-analyses and some of the larger clinical trials in the field.
- More large, high-quality, randomized, multicenter trials are required to improve our understanding of the impact of robotics and VR on stroke recovery.
- Robotics and VR can augment and complement conventional therapy and have the potential to be used as precision rehabilitation approaches.

INTRODUCTION

Stroke is a leading cause of disability, including reduced mobility, aphasia, depression, and cognitive decline.[1] Studies have estimated that the yearly cost of post-stroke care, including rehabilitation, ranges from 40 to 60K USD per patient in high-income countries, including the United States, Canada, Western Europe, Russia, Australia, and China (as of 2020).[2] Traditional rehabilitation methods rely on multidisciplinary teams (physiotherapy, occupational, recreational therapy, etc.) that often focus efforts on frequent and intense repetition to gradually improve skilled, goal-oriented movements.[3,4] Specifically, the frequency and duration of rehabilitation appear to be

[a] Department of Clinical Neurosciences, Cumming School of Medicine, University of Calgary, Calgary, Alberta, Canada; [b] Schulich School of Engineering: Department of Biomedical Engineering, University of Calgary, Calgary, Alberta, Canada; [c] Hotchkiss Brain Institute, University of Calgary, Calgary, Alberta, Canada; [d] Ablerta Children's Hospital Research Institute, University of Calgary, Calgary, Alberta, Canada; [e] Division of Physical Medicine and Rehabilitation, Cumming School of Medicine, University of Calgary, Calgary, Alberta, Canada
* Corresponding author. Department of Clinical Neurosciences, Foothills Medical Centre, 1403 29th Street Northwest, South Tower, Calgary, Alberta T2N 2T9, Canada.
E-mail address: spdukelo@ucalgary.ca

Phys Med Rehabil Clin N Am 35 (2024) 383–398
https://doi.org/10.1016/j.pmr.2023.06.026
pmr.theclinics.com
1047-9651/24/

important in facilitating better outcomes. In cases where remediation is not possible, the rehabilitation focus may turn toward teaching the patient to compensate for lost function using devices (eg, gait aids, orthoses). Despite the critical role of rehabilitation after a stroke, several challenges can limit its effectiveness. Common obstacles include access to care, resource constraints, coordination of multidisciplinary teams, and insurance coverage.[5] There is an increasing need to develop effective rehabilitation interventions that help stroke survivors regain independence. Therefore, integrating appropriate technology-based therapies may allow the potential for objective, repetitive, engaging, and personalized rehabilitation to help complement and augment traditional rehabilitation approaches.

Robots for Rehabilitation

The integration of robotics in rehabilitation began in the late 1990s and has steadily gained attention from researchers studying how to optimize stroke recovery.[6] For rehabilitation purposes, robotics can be categorized into end effectors and exoskeletons (**Fig. 1**). End effectors are designed to guide the distal parts of the limb to interact with the environment and perform specific tasks, such as grasping and reaching. In contrast, exoskeletons are designed to work with torque actuators that control joint movement and therefore can augment the movements of each joint they cross.[7] These systems enable the design of specific rehabilitation tasks and provide objective feedback through visual, motor/sensory, and cognitive mechanisms. Robotic devices tend to focus on either the upper or lower extremity and are employed to target improving motor function, patterns of muscular activity, range of motion, and in some cases enhanced activity and mobility in the community.[8] Although most studies have explored the use of robots in a therapeutic nature, they can also be used as an orthosis, replacing a particular body function.[9,10] Further, robots can be used to measure the kinematics and/or kinetics of movement to track changes in impairment over time.[11,12] This information can be critical to understanding therapy-induced improvements in impairment.

Upper-limb Robotics

Early studies of robotics in the upper-limb focused on their ability to provide a rehabilitative treatment intervention.[13] However, soon after their implementation as

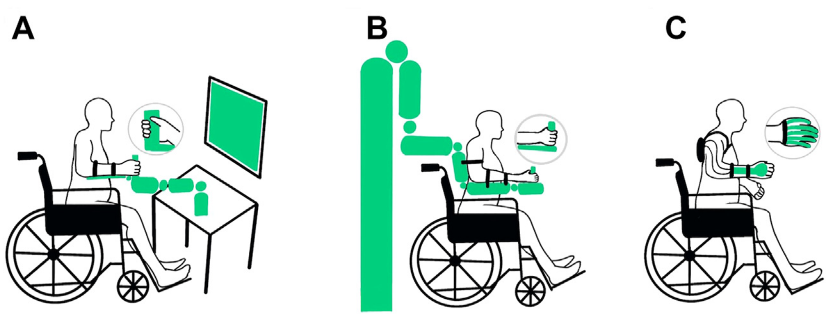

Fig. 1. Upper limb robotic solutions for stroke rehabilitation with stroke patient seated in a wheelchair (*black*) using (*A*) an end effector sometimes paired with a video screen (*green*) such as InMotion2,[20,21,23] NEREBOT,[84] Haptic Master,[85] ArmeoSpring,[86] and Bi-Manu Track[87]; (*B*) an exoskeleton (*green*) such as KINARM,[15] ARMin,[26] T-WREX,[88] and ARMOR[89]; (*C*) soft wearable hand robotic device (*green*) with a power supply backpack such as GloReha.[90] (Figure is adapted from Gassert and Dietz, with permission.[91])

rehabilitation tools, researchers and clinicians recognized their ability to act as assessment tools[14] to quantify various aspects of impairment. Conventional clinical assessments tend to be largely observer-based, ordinal scales, posing challenges related to floor and ceiling effects and reliability, robots, on the other hand, can allow for precise and accurate quantification of sensory-motor impairments,[15,16] spasticity,[17] kinaesthesia,[18,19] and proprioception.[11,12] A variety of robotic devices that have been used for assessment include the InMotion,[20–23] KINARM,[15] ARM Guide,[24] MIME,[25] and ArmIn[26] among others.

As mentioned above, a substantial focus in the early literature was the use of robots as a therapeutic tool. A 2018 Cochrane review included 45 randomized clinical trials (RCT), 9 robotic devices, and 1619 stroke patients and found high evidence supporting the use of robot-assisted arm therapy (RAAT) in improving overall arm function as measured by Upper Extremity Fugl-Meyer Assessment (UE-FM). Specifically, the author concluded that RAATs contributed to improvement in function, muscle strength, and performance of activities of daily living, with a caveat that there was high variability in training intensity (duration and frequency), the robotic device used, participant characteristics, and clinical outcomes.[27] Similarly, a network meta-analysis summarizing the effects of RAAT on motor function and activity[a] in upper-limb rehabilitation from 18 RCTs reported that the effectiveness of RAAT depended on 3 main factors: duration of intervention, level of impairment, and time since stroke.[28] Although RAAT was most effective in improving motor function as measured by UE-FM in subacute patients with severe to moderate impairments with 6 to 15 hours of intervention delivered, chronic patients with mild impairments benefited from RAAT with 15 to 30 hours of intervention delivered. However, RAAT did not result in significant improvements in activities of daily living (Barthel Index) when compared to conventional therapy. Despite these reviews suggesting chronic patients would benefit from RAAT, the largest clinical trial, the RATULS trial with 770 participants (largely chronic stroke) concluded that RAAT (delivered with the InMotion2 robot, 45 minutes session, three times a week, for 12 weeks) had no clinically meaningful functional improvements compared with conventional therapy (45 minutes a session, a minimum of 5 weeks, until rehabilitation goals were met).[29] Furthermore, another systematic review and meta-analysis of 11 RCTs in subacute stroke reported that the only requirement for effective upper-limb rehabilitation was highly intensive and repetitive movements, regardless of whether they were facilitated by robots or therapists.[30] A recommendation for future trials has been to carefully consider the optimal therapy dose and time since stroke in any ensuing RAAT studies.[31,32]

It is important to recognize that there were substantial differences in the types of robotic devices included in the above metanalyses.[27,28,30] Robots varied in their design and in what part of the upper extremity was targeted (ie, shoulder, elbow, wrist, hand, finger). A systematic review (149 participants, 5 trials) found exoskeletons to be more effective than end-effectors for finger-hand motor recovery.[33] In contrast, a larger review (2654 participants, 55 trials) compared the relative efficacy of 28 different types of robotic devices on activities of daily living, arm function, and strength and concluded that no one type of intervention (either unilateral or bilateral end-effector vs exoskeleton for distal vs proximal) was significantly better than the other.[34] Overall, there is weak evidence in the literature favoring either the exoskeletons or end effectors for improving arm function[35–37] but it is rare to see an actual head-to-head comparison of the robotic devices.

[a] By the International Classification of Functioning, Disability and Health (ICF) definition, activity is the execution of a task by an individual.

The integration of exoskeletons with noninvasive brain stimulation (through transcranial direct current stimulation [tDCS]), neuromuscular stimulation, and functional electrical stimulation has gained some attention in chronic stroke patient rehabilitation (368 patients, 10 trials)[38] with upper-limb impairment. Although there was some promise of functional improvements with wrist and hand components when RAAT is coupled with stimulation,[39,40] there was weak evidence to suggest that arm training is benefited by coupling RAAT with stimulation.[41] More high-quality studies are warranted to establish when to employ brain stimulation in rehabilitating upper extremities with RAAT.

In summary, although RAAT has demonstrated some promise as a tool for the assessment and treatment of the post-stroke upper extremity, there are still fundamental questions about the optimal dose and timing of administration. However, the same could be said of traditional stroke rehabilitation practice. The sheer number of devices and relative lack of comparative studies make navigating which robot might be best for a given patient challenging. Implementation into health care systems has proven challenging in some jurisdictions because of the initial expense of the device, reimbursement mechanisms for robotic therapy, and a lack of clear guidelines around best practices for integrating RAAT into clinical practice. The possibility of further augmenting RAAT with noninvasive brain stimulation or peripheral nerve stimulation remains an active area of research. Perhaps at present, RAAT is best viewed as a reasonable way to augment upper-limb therapy after stroke with much work to be done to facilitate and support clinical translation.

Lower-limb Robotics

Independent walking after a stroke is a predictor of autonomy and optimized quality-of-life outcomes.[42] Stroke-induced lower-limb impairments often involve an abnormal gait, impaired balance, asymmetric weight distribution (more weight on the unaffected side), and increased postural oscillation. Earlier studies in robot-assisted gait training (RAGT) focused largely on the use of devices that offered partial body weight support and incorporated a treadmill such as the Lokomat[43,44] or moved the patient's feet in an elliptical-like motion such as the Gait Trainer 1.[45] More recently, wearable exoskeletons (like the EksoGT,[46,47] ReWalk,[48] Indego,[49] or HAL[50]) are being clinically evaluated and adopted for stroke rehabilitation[51] (**Fig. 2**). RAGT devices have demonstrated the ability to allow patients to ambulate in a supported environment which might be challenging to accomplish without several human therapists assisting, particularly for those individuals with more severe lower-limb impairment. In some devices, a patient can be fully supported, and the robot can simply be used to move the limbs through a range of motion passively, while at other times the patient must initiate a movement to trigger the next step, making the rehabilitation more active in nature.

A recent meta-analysis, which included 15 studies, examined the effectiveness of using treadmill-based exoskeletons as an adjunct to conventional therapy for gait training, compared with the effectiveness of conventional therapy alone. Although the authors identified no significant differences in ambulatory function, walking speed, or walking endurance, they reported marked improvements in balance function and cadence in chronic stroke in the RAGT group.[52] Interestingly, this improvement in balance was not witnessed in studies where the robot only moved the patient's limbs passively, which suggests the importance of encouraging active movement during gait rehabilitation to maximize effectiveness.

Similar to RAAT, some authors have attempted to determine whether the type of device employed in RAGT may have an impact on outcomes. In a meta-analysis of 13

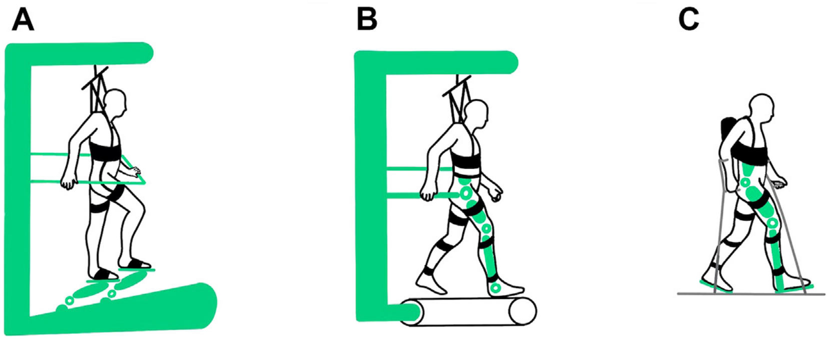

Fig. 2. Lower-limb robotics solutions for stroke rehabilitation with stroke patient walking (black): (*A*) on a gait training system (*green*) with body weight support (*black*) such as Gait Trainer 1,[45] G-EO,[92] GAR,[93] and Lexo[94]; (*B*) on a treadmill with an exoskeleton (*green*) and body weight support (*black*) such as Lokomat and LokomatPro; some commercially available devices as pictured in (*A*) and (*B*) may come with video display screens; (*C*) overground with forearm crutches (*black*) using a wearable exoskeleton (*green*) such as EksoGT,[43,44,46] ReWalk,[48] HAL,[50] Indego,[49] and SMA.[58] (Figure is adapted from Gassert and Dietz, with permission.[91])

studies, Bruni and colleagues[53] investigated the differences between exoskeletons (218 participants, 6 robots) and end effectors (469 participants, 7 robots) in RAGT across chronic (167 participants, 4 trials) and subacute (520 participants, 9 trials) stroke participants. Their observations indicate that, unlike exoskeletons, end-effector devices can independently improve walking speed in comparison to conventional therapy. However, this effect was statistically significant for subacute patients only, suggesting that non-ambulatory patients derive the most benefit from RAGT when robots support distal parts of the limb and mimic the stance and swing phases of gait within a few weeks from stroke.[53] Furthermore, exoskeletons have also been successful in reducing the perception of pain,[44,54] reducing spasticity,[55] improving muscle tone at the hip, knee, and ankle,[43,44] and maximizing the effectiveness of physiotherapists during gait training.[8]

A recent systematic review of 71 clinical trials investigated the design and clinical evaluation of nearly 25 commercially available wearable exoskeletons (as of 2021) for rehabilitating patients with either stroke, spinal cord injury, or other neurologic diseases.[56] They found that wearables can improve various aspects of lower-limb ambulation, including cadence, speed, and asymmetries in step length or stride length. RCTs comparing the SMA with functional training for stroke patients demonstrated significant increases in step length of the paretic leg,[57] endurance (6MWT),[58] balance,[58] cortical motor excitability of the paretic rectus femoris,[58] and reductions in asymmetry[57] (all cases, $P < .05$). Another RCT comparing a custom robotics-assisted ankle-foot orthosis (AFO) with a passive AFO in conventional therapy found that the robotic group showed significant improvements in vertical loading and braking forces on the affected side, as well as improved knee flexion on the unaffected side based on ground reaction data.[59] However, the adoption of wearable exoskeletons was often challenged by economic cost,[60,61] ergonomic issues,[62] and human-exoskeleton interaction based control issues.[63] The latter included the weight of the device that increased the metabolic cost of walking, the extensive time required for donning/doffing the device (up to 30 minutes), and the technical expertise required for implementing the use. The authors highlighted the lack of dynamic assist-as-needed algorithms and the use of deterministic algorithms to identify the various phases of gait as factors limiting the design of patient-centric rehabilitative interventions. These findings (both qualitative and quantitative) were recently confirmed by the ExStRA trial,[46] which used the EksoGT for stepping, weight shifting, and walking practice in a cohort of 36 first-time, subacute stroke patients. Results from the as-treated analysis of the ExStRA trial showed that patients who completed the exoskeleton regime had better gait, walking endurance, and walked more independently. However, therapists and patients also confirmed a steep learning curve, confusion, and intimidation in handling the device, lack of trained staff, and lack of therapy time outside the exoskeleton as limitations for implementing their use clinically. The therapists also acknowledged that the exoskeleton allowed early walking for individuals with severe stroke who would not be rehabilitated as early with conventional therapeutic approaches.[47]

Recently, RAGT has been coupled with noninvasive brain stimulation techniques to improve the efficacy of lower-limb rehabilitation.[38] In a randomized sample of 37 chronic stroke participants, Naro and colleagues[64] investigated the safety and efficacy of combining task-specific and repetitive RAGT through the LokomatPro with dual-site tDCS to restore interhemispheric balance. This study reported improvements in gait stability, balance, and walking endurance among patients who received brain stimulation during and after RAGT, as opposed to modulating cortical excitability before each RAGT session.[64] Another recent RCT used the Stride Management Assist (SMA) exoskeleton with 50 chronic stroke patients and concurrently manipulated the cortical motor excitability using transcranial magnetic stimulation (TMS).[58] This study concluded the SMA group had better endurance and higher absolute activity level (step count) on therapy days and observed larger changes in the corticomotor excitability of the paretic rectus femoris muscle.[58] Furthermore, by combining robotics with modulation of motor excitability, these studies have demonstrated the potential for using RAGT to target specific muscle groups (such as the hamstring, tibialis anterior, and quadriceps) to improve lower-limb strength and function.

In summary, the last few decades have produced some promising evidence for robotic therapy for lower-limb rehabilitation post-stroke, particularly for individuals with more severe gait impairments. That said, there are ongoing challenges with robot designs and control strategies in many devices that have limited uptake. Like RAAT, implementation has proven challenging in many centers because of the cost and technical training required for staff to operate the devices. Further technical optimizations, speeding up donning and doffing, and lessening the burden on clinicians trying to operate the robots may lead to more widespread adoption of these technologies into the health care system and homes.

Virtual Reality for Rehabilitation

VR is a set of computer-generated simulations that allow users to engage and interact with a simulated environment in a naturalistic fashion, resulting in a wide range of experiences from non-immersive, semi-immersive, and fully immersive[65] (**Fig. 3**). The adoption of VR to enhance the efficacy of conventional rehabilitative interventions[66] in stroke began in the 1990s,[67] with a primary focus on improving patient engagement,[68] and successful translation of the therapy from hospitals to homes.

A 2017 Cochrane review on VR for both upper- and lower-limb stroke rehabilitation included 2470 participants and 72 trials.[69] The authors suggested for the upper-limb (22 trials) that VR on its own was not superior to conventional therapy. However, when VR was used as an add-on to effectively increase the dose of therapy delivered, there were notable improvements in UE-FM scores amongst other outcomes. However, the

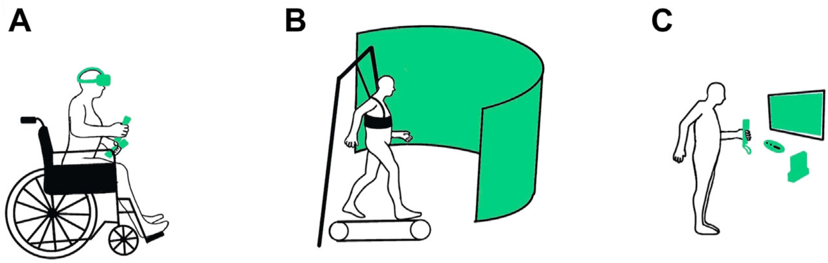

Fig. 3. VR solutions for stroke rehabilitation: (*A*) stroke patient seated in a wheelchair (*black*) with an immersive VR headset and VR controllers (*green*) such as Oculus,[95] HTC Vive[96]; (*B*) stroke patient on a treadmill with body weight support (*black*) in front of a semi-immersive VR screen (*green*) (eg, Motek GRAIL,[97] Motek CAREN,[98] Motek C-mill[99]); (*C*) stroke patient standing in front of a video screen holding a VR controller connected to non-immersive VR gaming systems (*green*) such as Xbox Kinect,[100] Playstation,[101] Nintendo Wii,[102] and Leap Motion.[103]

evidence was considered to come from low-quality studies (as ranked by GRADE). Recently, another systematic review (2271 participants, 50 trials) concluded that VR[b] was superior to conventional treatment for upper-limb impairment (UE-FM) and activities of daily living, but not for performance on Box and Block Test and Wolf Motor Function Test.[70] The consistent criticism in both these reviews was that VR trials are often low-quality studies that have a high risk of bias.

In the lower-limb literature, a large systematic review (2328 participants, 61 trials)[71] comparing VR gait training with body weight support gait training concluded that VR gait training helps improve performance on balance battery assessments and dynamic balance, but not steady-state balance. Two meta-analyses (809 participants, 32 studies[72]; 337 participants, 18 trials[73]) compared VR with treadmill-based training, or RAGT for chronic stroke patients and reported significant improvements in cadence, stride length, and gait speed in VR-based gait training. A smaller systematic review (183 participants, 11 trials, 2 RAGT trials)[74] with similar results suggested a minimum of 10 sessions are required to derive any meaningful changes in motor function, with immersive VR being more effective than semi- or non-immersive VR.

Some studies have examined the potential impact of VR on cognitive function. A large meta-analysis of 87 clinical trials involving 3540 participants examined the ability of VR to improve upper- and lower-limb function, activities of daily living, and cognition. In this analysis, Zhang and colleagues[75] found that only 7 studies reported on the Mini-Mental State Examination, which included 210 participants. Despite the low sample size and moderate heterogeneity, Mini-Mental State scores were higher in the VR groups compared with conventional therapy groups within 4 weeks of the intervention. Another smaller meta-analysis (196 patients, 8 trials)[76] that specifically investigated the effect of VR on post-stroke cognition alone found no significant differences between groups who received VR alone and those who received a combination of VR and conventional therapy.

In summary, there have been many studies examining the use of VR for stroke rehabilitation. Critics have consistently suggested higher-quality studies are needed to

[b] In this paper, VR, augmented reality, and mixed reality technologies were compared with conventional therapy for upper-limb. Of these, the VR technologies reviewed were largely off-the shelf solutions like the Nintendo Wii and Xbox Kinect.

better assess the efficacy and clinical utility. The studies that do exist have been conducted with many different VR systems and various levels of immersiveness. Several existing trials were conducted using off-the-shelf solutions like Xbox Kinect, Nintendo Wii, and PlayStation, to study the effects of gaming-based VR in rehabilitation programs.[77,78] These VR systems cost as little as a few hundred dollars and are a potentially promising solution for improving the patient's rehabilitation experience outside the clinical setting. Head-to-head comparisons of these less costly VR approaches and more complex, fully immersive approaches specifically designed for stroke rehabilitation are scarce. More studies are needed to determine how important the level of immersiveness is in stroke recovery.

The Potential of Combining Robotics and Virtual Reality

Given that rehabilitation is a complex, multifactorial process, Clarke and colleagues[79] investigated the efficacy of individually using robotics and VR as an adjunct to conventional therapy versus the combination of robotics and VR (Robotic Therapy [RT] + CT, VR + CT vs RT + VR + CT). The authors suggested the benefit of coupling robotics with VR was the ability to facilitate repetitive, high-intensity and task-specific interventions while also engaging patients, reducing frustration and fatigue, while providing visual and cognitive feedback in a gamified manner, thus enhancing the overall therapy experience.[79]

In a systematic review by Mubin and colleagues[80] of 30 studies that employed VR coupled with robotics (VR + RT) showed that the VR, augmented reality, or gamification technologies aided in the transition of exoskeleton-based rehabilitation from hospitals to homes. In assessing the effectiveness of VR + RT to improve health-related quality of life across different neurologic conditions (RT = 52 studies, VR + RT = 18, largely pilot studies), Zanatta and colleagues[81] found that in comparison to using robotics alone, the VR + RT significantly improved quality of life in patients with stroke, despite the shorter therapy and session duration. Most of the studies considered for this used non-immersive VR mediated through screens and monitors. As a result, it has been suggested that the combination of VR + RT has the potential to stimulate motor learning and neuroplasticity better than using either in isolation.[79]

DISCUSSION

In this review, we have described different robotic and VR applications in stroke rehabilitation and briefly reviewed the existing evidence for their use. Broadly speaking, both robotics and VR have demonstrated some level of efficacy in several studies. However, results should be interpreted with caution as much of the evidence comes from small clinical trials with significant heterogeneity in the devices used, patient characteristics, and outcome measures employed.

In examining the literature, there are frequent discrepancies between the findings of large meta-analyses and some of the larger individual clinical trials. We suspect this may be due to several factors. Smaller trials are common in the literature and impact the results of meta-analyses, despite the risk of these trials being underpowered and having a higher risk of bias. Multiple systematic reviews remarked on the lower quality ratings of the trials included, and most trials tended to employ a single device. One would suspect the type of device might impact the outcome, although some suggestions have been that this may not be the case.[34] Lastly, patient factors such as time since stroke and stroke location can drastically influence a trial outcome. In most systematic reviews and meta-analyses, but not all, different stroke subtypes and/or stroke chronicity (eg, subacute, chronic) are collapsed together despite differences in expected outcomes. Ultimately, we need to consider employing larger, high-quality, randomized, multicenter trials with appropriate control groups to fully understand the efficacy of device-specific robotic interventions tailored to specific patient cohorts.

Despite the challenges above, robotics and VR have more evidence behind them than some other common rehabilitation interventions (eg, splinting for spasticity), yet their adoption by clinicians and the healthcare system in many parts of the world is limited. To encourage easy adoption, the technical design of robotic devices needs to consider the challenges that both therapists and patients face when learning to use them. Early career therapists in Canada (n = 127) reported a lack of awareness of robotic (62.2%) and VR-based (37%) interventions as a primary reason for not adopting them in clinical practice, along with a lack of access (RT: 21.2%; VR: 44% did not have access), increased cost (RT: 11%; VR:12.6%), and lack of time (RT: 0.04%; VR: 0.1%) to use emerging technologies.[82] These challenges exist despite the emphasis on evidence-based practice in post-secondary training institutions, resulting in a drastic need for knowledge translation that can drive the implementation of technology-based solutions in the clinic. When evaluating the cost-effectiveness of VR + RT technologies, it is important to consider not only the upfront purchasing cost but also the operational cost of administering therapy. For example, although the hardware for VR solutions is affordable, ongoing expenses for software development and maintenance can be significant. Additionally, in some countries, a clear reimbursement pathway for interventions is lacking, which limits their uptake in the clinical setting.

FUTURE PROSPECTS

Although the effectiveness of robotics and VR (or a combination of both) in comparison to conventional care remains mixed, these technologies can be used to facilitate and augment early, intensive, and patient-centered therapy. Robotics has the potential to be an adjunct to one-on-one therapy, especially in clinical settings with limited availability of skilled and qualified therapists if someone has the skills to operate the robot. Furthermore, robotics can minimize the demand for therapists to facilitate repetitive movements and thereby reduce potential injuries.[83] Both VR and robotics have demonstrated their ability to safely and effectively engage patients with severe impairments earlier in therapy than is possible with conventional care alone. Furthermore, the emerging field of wearables combined with affordable VR solutions can enhance the probability of rehabilitation to extend beyond the clinical setting, allowing patients to continue their therapy comfortably at home.

The field of integrated robotics and multimodal stimulation in therapy is still in its infancy. However, with ongoing advancements in the development of more human-like movements and immersive mixed-reality headsets, the potential for adoption in stroke rehabilitation and improving activities of daily living is encouraging. As the technology continues to evolve, researchers and clinicians must work together across multiple centers to gather high-quality evidence to support and optimize the integration of these emerging solutions into clinical practice.

More importantly, there is also a wealth of data on the severity of impairment and patient engagement that these robotics and VR solutions capture. This creates a tremendous opportunity to better understand the impairment and recovery process following a stroke. It also allows clinicians the potential to integrate kinematic and kinetic information into clinical care and tailor therapy to the individual patient, paving the way for precision rehabilitation.

SUMMARY

This review highlights the existing evidence for using robotics and VR in stroke rehabilitation. Although there are technical and cost-related challenges in the widespread adoption of robotics and VR in stroke rehabilitation, these emerging solutions offer a unique advantage by capturing a wealth of data on patient impairment, engagement, and comfort. This can aid in a precision rehabilitation approach, but it can also help address staff shortages by delivering therapy effectively in clinics where human resources may be scarce.

CLINICS CARE POINTS

- Robotic devices can be helpful in increasing repetitive training for stroke survivors retraining their upper and lower limbs. Appropriate patient and device selection would seem to be important but at present, little data exists to guide these decisions.
- VR can be helpful to supplement ongoing rehabilitation to achieve greater gains and is often combined in studies with other technology-based tools such as robotics or treadmills.
- At present, several robotic and VR devices are available, but there is little data comparing different devices.

FUNDING

DR and AB are funded by the Cumming Medical Research Fund from the University of Calgary and the Hotchkiss Brain Insitute Graduate Studentship award respectively.

DISCLOSURE

SPD: Speakers fees from Abbvie, Merz. He has been part of advisory boards for Ipsen Pharmaceuticals.Consultancy fees from Prometheus Medical.Operating grants from the University of Calgary, Canadian Institutes of Health Research, Heart and Stroke Foundation, and Brain Canada.He has collaborated with Red Iron Labs on the development of a virtual reality intervention for stroke rehabilitation. **DR and AB**: No disclosures. **KLK**: Dr. Kelly Kaiser is a founder and holds equity in HEMOtx.

REFERENCES

1. Katan M, Luft A. Global burden of stroke. Semin Neurol 2018;38(2):208–11.
2. Strilciuc S, Grad DA, Radu C, et al. The economic burden of stroke: a systematic review of cost of illness studies. J Med Life 2021;14(5):606–19.
3. Johansson BB. Current trends in stroke rehabilitation. a review with focus on brain plasticity. Acta Neurol Scand 2011;123(3):147–59.
4. Dobkin BH. Strategies for stroke rehabilitation. Lancet Neurol 2004;3(9):528–36.
5. Stinear CM, Lang CE, Zeiler S, et al. Advances and challenges in stroke rehabilitation. Lancet Neurol 2020;19(4):348–60.
6. Aisen ML, Krebs HI, Hogan N, et al. The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke. Arch Neurol 1997;54(4):443–6.
7. Chang WH, Kim YH. Robot-assisted therapy in stroke rehabilitation. J Stroke 2013;15(3):174–81.
8. Cho JE, Yoo JS, Kim KE, et al. Systematic Review of Appropriate Robotic Intervention for Gait Function in Subacute Stroke Patients. BioMed Res Int 2018;2018:e4085298.

9. Iida S, Kawakita D, Fujita T, et al. Exercise using a robotic knee orthosis in stroke patients with hemiplegia. J Phys Ther Sci 2017;29(11):1920–4.
10. Chen A, Winterbottom L, Park S, et al. Thumb stabilization and assistance in a robotic hand orthosis for post-stroke hemiparesis. IEEE Robot Autom Lett 2022; 7(3):8276–82.
11. Scott SH, Dukelow SP. Potential of robots as next-generation technology for clinical assessment of neurological disorders and upper-limb therapy. J Rehabil Res Dev 2011;48(4):335–53.
12. Semrau JA, Herter TM, Scott SH, et al. Examining differences in patterns of sensory and motor recovery after stroke with robotics. Stroke 2015;46(12):3459–69.
13. Burgar CG, Lum PS, Shor PC, et al. Development of robots for rehabilitation therapy: the Palo Alto VA/Stanford experience. J Rehabil Res Dev 2000;37(6): 663–73.
14. Reinkensmeyer DJ, Schmit BD, Rymer WZ. Mechatronic assessment of arm impairment after chronic brain injury. Technol Health Care 1999;7(6):431–5.
15. Coderre AM, Amr AZ, Dukelow SP, et al. Assessment of upper-limb sensorimotor function of subacute stroke patients using visually guided reaching. Neurorehabilitation Neural Repair 2010;24(6):528–41.
16. Dukelow SP, Herter TM, Moore KD, et al. Quantitative assessment of limb position sense following stroke. Neurorehabilitation Neural Repair 2010;24(2): 178–87.
17. de-la-Torre R, Oña ED, Balaguer C, et al. Robot-aided systems for improving the assessment of upper limb spasticity: a systematic review. Sensors 2020;20(18): 5251.
18. Kenzie JM, Semrau JA, Findlater SE, et al. Localization of impaired kinesthetic processing post-stroke. Front Hum Neurosci 2016;10:505.
19. Semrau JA, Herter TM, Scott SH, et al. Differential loss of position sense and kinesthesia in sub-acute stroke. Cortex J Devoted Study Nerv Syst Behav 2019; 121:414–26.
20. Bosecker C, Dipietro L, Volpe B, et al. Kinematic robot-based evaluation scales and clinical counterparts to measure upper limb motor performance in patients with chronic stroke. Neurorehabilitation Neural Repair 2010;24(1):62–9.
21. Rohrer B, Fasoli S, Krebs HI, et al. Movement smoothness changes during stroke recovery. J Neurosci 2002;22(18):8297–304.
22. Dipietro L, Krebs HI, Fasoli SE, et al. Changing motor synergies in chronic stroke. J Neurophysiol 2007;98(2):757–68.
23. Palazzolo JJ, Ferraro M, Krebs HI, et al. Stochastic estimation of arm mechanical impedance during robotic stroke rehabilitation. IEEE Trans Neural Syst Rehabil Eng Publ IEEE Eng Med Biol Soc 2007;15(1):94–103.
24. Reinkensmeyer DJ, Dewald JP, Rymer WZ. Guidance-based quantification of arm impairment following brain injury: a pilot study. IEEE Trans Rehabil Eng Publ IEEE Eng Med Biol Soc 1999;7(1):1–11.
25. Lum PS, Burgar CG, Kenney DE, et al. Quantification of force abnormalities during passive and active-assisted upper-limb reaching movements in post-stroke hemiparesis. IEEE Trans Biomed Eng 1999;46(6):652–62.
26. Guidali M, Schmiedeskamp M, Klamroth V, Riener R. Assessment and training of synergies with an arm rehabilitation robot. IEEE; 2009. p. 772–6.
27. Mehrholz J, Pohl M, Platz T, et al. Electromechanical and robot-assisted arm training for improving activities of daily living, arm function, and arm muscle strength after stroke. Cochrane Database Syst Rev 2018;9. https://doi.org/10.1002/14651858.CD006876.pub5.

28. Everard G, Declerck L, Detrembleur C, et al. New technologies promoting active upper limb rehabilitation after stroke: an overview and network meta-analysis. Eur J Phys Rehabil Med 2022;58(4).
29. Rodgers H, Shaw L, Bosomworth H, et al. Robot Assisted Training for the Upper Limb after Stroke (RATULS): study protocol for a randomised controlled trial. Trials 2017;18(1):340.
30. Chien WT, Chong YY, Tse MK, et al. Robot-assisted therapy for upper-limb rehabilitation in subacute stroke patients: a systematic review and meta-analysis. Brain Behav 2020;10(8):e01742.
31. Bernhardt J, Mehrholz J. Robotic-assisted training after stroke: RATULS advances science. Lancet 2019;394(10192):6–8.
32. Rodgers H, Bosomworth H, Krebs HI, et al. Robot assisted training for the upper limb after stroke (RATULS): a multicentre randomised controlled trial. Lancet 2019;394(10192):51–62.
33. Moggio L, de Sire A, Marotta N, et al. Exoskeleton versus end-effector robot-assisted therapy for finger-hand motor recovery in stroke survivors: systematic review and meta-analysis. Top Stroke Rehabil 2022;29(8):539–50.
34. Mehrholz J, Pollock A, Pohl M, et al. Systematic review with network meta-analysis of randomized controlled trials of robotic-assisted arm training for improving activities of daily living and upper limb function after stroke. J NeuroEngineering Rehabil 2020;17:83.
35. Conroy SS, Wittenberg GF, Krebs HI, et al. Robot-assisted arm training in chronic stroke: addition of transition-to-task practice. Neurorehabilitation Neural Repair 2019;33(9):751–61.
36. Platz T, Eickhof C, van Kaick S, et al. Impairment-oriented training or Bobath therapy for severe arm paresis after stroke: a single-blind, multicentre randomized controlled trial. Clin Rehabil 2005;19(7):714–24.
37. Krebs HI, Mernoff S, Fasoli SE, et al. A comparison of functional and impairment-based robotic training in severe to moderate chronic stroke: a pilot study. NeuroRehabilitation 2008;23(1):81–7.
38. Comino-Suárez N, Moreno JC, Gómez-Soriano J, et al. Transcranial direct current stimulation combined with robotic therapy for upper and lower limb function after stroke: a systematic review and meta-analysis of randomized control trials. J Neuroengineering Rehabil 2021;18(1):148.
39. Hsu HY, Chiu HY, Kuan TS, et al. Robotic-assisted therapy with bilateral practice improves task and motor performance in the upper extremities of chronic stroke patients: a randomised controlled trial. Aust Occup Ther J 2019;66(5):637–47.
40. Kuo LC, Yang KC, Lin YC, et al. Internet of things (iot) enables robot-assisted therapy as a home program for training upper limb functions in chronic stroke: a randomized control crossover study. Arch Phys Med Rehabil 2023;104(3): 363–71.
41. Morone G, Capone F, Iosa M, et al. May dual transcranial direct current stimulation enhance the efficacy of robot-assisted therapy for promoting upper limb recovery in chronic stroke? Neurorehabilitation Neural Repair 2022;36(12): 800–9.
42. Kinoshita S, Abo M, Okamoto T, et al. Utility of the revised version of the ability for basic movement scale in predicting ambulation during rehabilitation in post-stroke patients. J Stroke Cerebrovasc Dis 2017;26(8):1663–9.
43. van Nunen MPM, Gerrits KHL, Konijnenbelt M, et al. Recovery of walking ability using a robotic device in subacute stroke patients: a randomized controlled study. Disabil Rehabil Assist Technol 2015;10(2):141–8.

44. Tamburella F, Moreno JC, Herrera Valenzuela DS, et al. Influences of the biofeedback content on robotic post-stroke gait rehabilitation: electromyographic vs joint torque biofeedback. J Neuroengineering Rehabil 2019;16(1):95.
45. Hesse S, Werner C, von Frankenberg S, et al. Treadmill training with partial body weight support after stroke. Phys Med Rehabil Clin N Am 2003;14(1 Supplement):S111–23.
46. Louie DR, Mortenson WB, Durocher M, et al. Exoskeleton for post-stroke recovery of ambulation (ExStRA): study protocol for a mixed-methods study investigating the efficacy and acceptance of an exoskeleton-based physical therapy program during stroke inpatient rehabilitation. BMC Neurol 2020;20(1):35.
47. Louie DR, Mortenson WB, Durocher M, et al. Efficacy of an exoskeleton-based physical therapy program for non-ambulatory patients during subacute stroke rehabilitation: a randomized controlled trial. J Neuroengineering Rehabil 2021; 18(1):149.
48. Awad LN, Esquenazi A, Francisco GE, et al. The ReWalk ReStore™ soft robotic exosuit: a multi-site clinical trial of the safety, reliability, and feasibility of exosuit-augmented post-stroke gait rehabilitation. J Neuroengineering Rehabil 2020; 17(1):80.
49. Tefertiller C, Hays K, Jones J, et al. Initial outcomes from a multicenter study utilizing the indego powered exoskeleton in spinal cord injury. Top Spinal Cord Inj Rehabil 2018;24(1):78–85.
50. Nilsson A, Vreede KS, Häglund V, et al. Gait training early after stroke with a new exoskeleton–the hybrid assistive limb: a study of safety and feasibility. J Neuroengineering Rehabil 2014;11:92.
51. Hobbs B, Artemiadis P. A review of robot-assisted lower-limb stroke therapy: unexplored paths and future directions in gait rehabilitation. Front Neurorobotics 2020;14:19.
52. Zhu YH, Ruan M, Yun RS, et al. Is leg-driven treadmill-based exoskeleton robot training beneficial to poststroke patients: a systematic review and meta-analysis. Am J Phys Med Rehabil 2023;102(4):331–9.
53. Bruni MF, Melegari C, De Cola MC, et al. What does best evidence tell us about robotic gait rehabilitation in stroke patients: a systematic review and meta-analysis. J Clin Neurosci 2018;48:11–7.
54. Zhang X, Yue Z, Wang J. Robotics in lower-limb rehabilitation after stroke. Behav Neurol 2017;2017:3731802.
55. Shakti D, Mathew L, Kumar N, et al. Effectiveness of robo-assisted lower limb rehabilitation for spastic patients: a systematic review. Biosens Bioelectron 2018;117:403–15.
56. Rodríguez-Fernández A, Lobo-Prat J, Font-Llagunes JM. Systematic review on wearable lower-limb exoskeletons for gait training in neuromuscular impairments. J Neuroengineering Rehabil 2021;18(1):22.
57. Buesing C, Fisch G, O'Donnell M, et al. Effects of a wearable exoskeleton stride management assist system (SMA®) on spatiotemporal gait characteristics in individuals after stroke: a randomized controlled trial. J NeuroEngineering Rehabil 2015;12(1):69.
58. Jayaraman A, O'Brien MK, Madhavan S, et al. Stride management assist exoskeleton vs functional gait training in stroke: A randomized trial. Neurology 2019;92(3):e263–73.
59. Yeung LF, Ockenfeld C, Pang MK, et al. Randomized controlled trial of robot-assisted gait training with dorsiflexion assistance on chronic stroke patients wearing ankle-foot-orthosis. J NeuroEngineering Rehabil 2018;15(1):51.

60. Carpino G, Pezzola A, Urbano M, et al. Assessing effectiveness and costs in robot-mediated lower limbs rehabilitation: a meta-analysis and state of the art. J Healthc Eng 2018;2018:7492024.
61. Lo K, Stephenson M, Lockwood C. The economic cost of robotic rehabilitation for adult stroke patients: a systematic review. JBI Database Syst Rev Implement Rep 2019;17(4):520–47.
62. Bhardwaj S, Khan AA, Muzammil M. Lower limb rehabilitation robotics: The current understanding and technology. Work Read Mass 2021;69(3):775–93.
63. Campagnini S, Liuzzi P, Mannini A, et al. Effects of control strategies on gait in robot-assisted post-stroke lower limb rehabilitation: a systematic review. J NeuroEngineering Rehabil 2022;19:52.
64. Naro A, Billeri L, Manuli A, et al. Breaking the ice to improve motor outcomes in patients with chronic stroke: a retrospective clinical study on neuromodulation plus robotics. Neurol Sci Off J Ital Neurol Soc Ital Soc Clin Neurophysiol 2021; 42(7):2785–93.
65. Gigante MA. Virtual reality: definitions, history and applications. In: Virtual reality systems. Academic Press; 1993. p. 3–14.
66. Bergmann J, Krewer C, Bauer P, et al. Virtual reality to augment robot-assisted gait training in non-ambulatory patients with a subacute stroke: a pilot randomized controlled trial. Eur J Phys Rehabil Med 2018;54(3):397–407.
67. Cruz-Neira C, Sandin DJ, DeFanti TA, et al. The CAVE: audio visual experience automatic virtual environment. Commun ACM 1992;35(6):64–72.
68. Yoshida T, Otaka Y, Osu R, et al. Motivation for rehabilitation in patients with subacute stroke: a qualitative study. Front Rehabil Sci 2021;2.
69. Laver KE, Lange B, George S, et al. Virtual reality for stroke rehabilitation. Cochrane Database Syst Rev 2017;11.
70. Leong SC, Tang YM, Toh FM, et al. Examining the effectiveness of virtual, augmented, and mixed reality (VAMR) therapy for upper limb recovery and activities of daily living in stroke patients: a systematic review and meta-analysis. J Neuroengineering Rehabil 2022;19(1):93.
71. Lyu T, Yan K, Lyu J, et al. Comparative efficacy of gait training for balance outcomes in patients with stroke: A systematic review and network meta-analysis. Front Neurol 2023;14.
72. Virtual reality training enhances gait poststroke: a systematic review and meta-analysis. Ann N Y Acad Sci 2020;1478(1):18–42.
73. De Keersmaecker E, Lefeber N, Geys M, et al. Virtual reality during gait training: does it improve gait function in persons with central nervous system movement disorders? A systematic review and meta-analysis. NeuroRehabilitation 2019; 44(1):43–66.
74. Luque-Moreno C, Ferragut-Garcías A, Rodríguez-Blanco C, et al. A decade of progress using virtual reality for poststroke lower extremity rehabilitation: systematic review of the intervention methods. BioMed Res Int 2015;2015:342529.
75. Zhang B, Li D, Liu Y, et al. Virtual reality for limb motor function, balance, gait, cognition and daily function of stroke patients: a systematic review and meta-analysis. J Adv Nurs 2021;77(8):3255–73.
76. Wiley E, Khattab S, Tang A. Examining the effect of virtual reality therapy on cognition post-stroke: a systematic review and meta-analysis. Disabil Rehabil Assist Technol 2022;17(1):50–60.
77. Saposnik G, Cohen LG, Mamdani M, et al. Efficacy and safety of non-immersive virtual reality exercising in stroke rehabilitation (EVREST): a randomised, multicentre, single-blind, controlled trial. Lancet Neurol 2016;15(10):1019–27.

78. Thomson K, Pollock A, Bugge C, et al. Commercial gaming devices for stroke upper limb rehabilitation: a survey of current practice. Disabil Rehabil Assist Technol 2016;11(6):454–61.
79. Clark WE, Sivan M, O'Connor RJ. Evaluating the use of robotic and virtual reality rehabilitation technologies to improve function in stroke survivors: A narrative review. J Rehabil Assist Technol Eng 2019;6. https://doi.org/10.1177/2055668319863557. 2055668319863557.
80. Mubin O, Alnajjar F, Jishtu N, et al. Exoskeletons with virtual reality, augmented reality, and gamification for stroke patients' rehabilitation: systematic review. JMIR Rehabil Assist Technol 2019;6(2):e12010.
81. Zanatta F, Farhane-Medina NZ, Adorni R, et al. Combining robot-assisted therapy with virtual reality or using it alone? A systematic review on health-related quality of life in neurological patients. Health Qual Life Outcomes 2023;21(1):18.
82. McIntyre A, Viana R, Cao P, et al. A national survey of evidence-based stroke rehabilitation intervention use in clinical practice among Canadian occupational therapists. NeuroRehabilitation 2023;52(3):463–75.
83. Glover W. Work-related strain injuries in physiotherapists: prevalence and prevention of musculoskeletal disorders. Physiotherapy 2002;88(6):364–72.
84. Masiero S, Armani M, Ferlini G, et al. Randomized trial of a robotic assistive device for the upper extremity during early inpatient stroke rehabilitation. Neurorehabilitation Neural Repair 2014;28(4):377–86.
85. Timmermans AA, Lemmens RJ, Monfrance M, et al. Effects of task-oriented robot training on arm function, activity, and quality of life in chronic stroke patients: a randomized controlled trial. J NeuroEngineering Rehabil 2014;11:45.
86. Olczak A, Truszczyńska-Baszak A, Stępień A. The use of armeo®spring device to assess the effect of trunk stabilization exercises on the functional capabilities of the upper limb—an observational study of patients after stroke. Sensors 2022;22(12):4336.
87. Wu C, Yang C, Chen Mde, et al. Unilateral versus bilateral robot-assisted rehabilitation on arm-trunk control and functions post stroke: a randomized controlled trial. J NeuroEngineering Rehabil 2013;10(1):35.
88. Housman SJ, Scott KM, Reinkensmeyer DJ. A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis. Neurorehabilitation Neural Repair 2009;23(5):505–14.
89. Mayr A, Kofler M, Saltuari L. [ARMOR: an electromechanical robot for upper limb training following stroke. A prospective randomised controlled pilot study]. Handchir Mikrochir Plast Chir Organ Deutschsprachigen Arbeitsgemeinschaft Handchir Organ Deutschsprachigen Arbeitsgemeinschaft Mikrochir Peripher Nerven Gefasse Organ V 2008;40(1):66–73.
90. Polygerinos P, Wang Z, Galloway KC, et al. Soft robotic glove for combined assistance and at-home rehabilitation. Robot Auton Syst 2015;73:135–43.
91. Gassert R, Dietz V. Rehabilitation robots for the treatment of sensorimotor deficits: a neurophysiological perspective. J NeuroEngineering Rehabil 2018;15(1):46.
92. Hesse S, Tomelleri C, Bardeleben A, et al. Robot-assisted practice of gait and stair climbing in nonambulatory stroke patients. J Rehabil Res Dev 2012;49(4):613–22.
93. Ochi M, Wada F, Saeki S, et al. Gait training in subacute non-ambulatory stroke patients using a full weight-bearing gait-assistance robot: A prospective, randomized, open, blinded-endpoint trial. J Neurol Sci 2015;353(1–2):130–6.

94. End-effector-based Gaittrainer | LEXO®. Tyromotion. Available at: https://tyromotion.com/en/products/lexo/. Accessed May 1, 2023.
95. Ronchi R, Perez-Marcos D, Giroux A, et al. Use of immersive virtual reality to detect unilateral spatial neglect in chronic stroke. Ann Phys Rehabil Med 2018;61:e90–1.
96. Mekbib DB, Zhao Z, Wang J, et al. Proactive motor functional recovery following immersive virtual reality-based limb mirroring therapy in patients with subacute stroke. Neurother J Am Soc Exp Neurother 2020;17(4):1919–30.
97. Bahadori S, Williams JM, Wainwright TW. Lower limb kinematic, kinetic and spatial-temporal gait data for healthy adults using a self-paced treadmill. Data Brief 2021;34:106613.
98. Isaacson BM, Swanson TM, Pasquina PF. The use of a computer-assisted rehabilitation environment (CAREN) for enhancing wounded warrior rehabilitation regimens. J Spinal Cord Med 2013;36(4):296–9.
99. Timmermans C, Roerdink M, Meskers CGM, et al. Walking-adaptability therapy after stroke: results of a randomized controlled trial. Trials 2021;22(1):923.
100. Park DS, Lee DG, Lee K, et al. Effects of virtual reality training using xbox kinect on motor function in stroke survivors: a preliminary study. J Stroke Cerebrovasc Dis 2017;26(10):2313–9.
101. Yavuzer G, Senel A, Atay MB, et al. “Playstation eyetoy games'” improve upper extremity-related motor functioning in subacute stroke: a randomized controlled clinical trial. Eur J Phys Rehabil Med 2008;44(3):237–44.
102. Lee MM, Shin DC, Song CH. Canoe game-based virtual reality training to improve trunk postural stability, balance, and upper limb motor function in subacute stroke patients: a randomized controlled pilot study. J Phys Ther Sci 2016;28(7):2019–24.
103. Wang ZR, Wang P, Xing L, et al. Leap Motion-based virtual reality training for improving motor functional recovery of upper limbs and neural reorganization in subacute stroke patients. Neural Regen Res 2017;12(11):1823–31.