Post-stroke upper limb rehabilitation using virtual reality interventions: Do outcome measures assess extent or type of motor improvement?

Sandeep K Subramanian
Department of Physical Therapy, School of Health Professions
UT Health San Antonio
San Antonio, TX, USA
subramanias3@uthscsa.edu
0000-0002-5972-1588

Mackenzie K Cross
Department of Physical Therapy, School of Health Professions
UT Health San Antonio
San Antonio, TX, USA
crossmk@livemail.uthscsa.edu

Cole S Hirschhauser
Department of Physical Therapy, School of Health Professions
UT Health San Antonio
San Antonio, TX, USA
hirschhauser@livemail.uthscsa.edu

Vineet BK Johnson
School of Kinesiology, Lakehead University
Thunder Bay, ON, Canada
vinbenj@gmail.com

Timothy A Reistetter
Department of Occupational Therapy
School of Health Professions
UT Health San Antonio
San Antonio, TX, USA
reistetter@uthscsa.edu
0000-0003-1732-5533

***Abstract*— Post-stroke upper limb motor improvement continues to remain sub-optimal in a significant proportion of individuals sustaining a stroke. Efforts to enhance UL motor improvement have led to the use of evidence-based interventions including virtual reality technology. The effects of interventions on motor impairments, activity limitations and participation restrictions are commonly assesses using clinical outcomes. Majority of the clinical outcomes focus on the extent of motor improvement (i.e. how much). Information on the type (i.e. how) of recovery can be obtained by using a selected few clinical outcomes and movement pattern kinematic measures. The study objective was to characterize the outcomes used to assess the effects of virtual reality interventions in terms of quantifying the extent and type of upper limb motor improvement. We reviewed the published literature on the effects of virtual reality (VR) based interventions to enhance UL motor improvements. Outcomes from the retrieved studies were initially classified under the appropriate International Classification of Functioning categories. We then categorized the outcomes into those quantifying into type or extent of motor improvement based on existing evidence. We found 100 papers that investigated the effects of virtual reality interventions to enhance post-stroke UL motor improvement. Forty two different outcome measures were used across the 100 studies. Seventeen different outcomes assessed impairments, 16 were used to measure activity limitations and 6 measured participation restrictions and the effects of contextual factors. The Fugl Meyer Assessment, Wolf Motor Function Test and Stroke Impact Scale were most commonly used across the three categories. Of the retrieved 100 studies, 48 used an outcome that considered the type of recovery. Although a smaller proportion, 17 studies included outcomes of movement patterns. The use of outcomes considering the type of recovery is steadily increasing in studies using VR for post-stroke UL rehabilitation.**

Keywords — outcomes, kinematics, recovery, compensation, arm

I. Introduction

Stroke continues to be a global burden and a leading cause of adult disability [1]. Upper limb (UL) hemiparesis is one of the most disabling consequences of a stroke [2]. It often results in an impaired ability to successfully perform daily life activities (ADL) using the more-affected side, which often persists into the chronic stage [3]. Despite the availability of high-quality evidence, achieving maximal levels of UL motor improvement continues to remain a challenge [3]. Efforts to enhance UL motor improvements have led to incorporation of evidence-based interventions including robotics and virtual reality (VR) technologies [4, 5].

Inherent to the successful application of any intervention is the choice of the appropriate outcome measure to assess improvement. In post-stroke UL rehabilitation, outcomes are used to assess the severity of motor impairments, limitations in ADL performance as well as participation restrictions [6]. A wide variety of measures are available to assess issues across all three levels of the International Classification of Functioning (ICF) [7, 8]. On the other hand, the wide variation in the choice of measures also leads to issues in the synthesis of research findings [9]. This has prompted efforts to standardize the use of assessments to be able to better compare the effects of the same intervention across different studies. Recommendations are now available on the most suitable UL measures to be used in studies to enable comparisons [10].

These recommendations [10] suggest using the Fugl-Meyer Assessment (FMA) and Action Research Arm Test (ARAT) as outcomes at the impairment and activity limitation levels of the ICF [11]. Both measures have well established psychometric properties and standardized instructions for test administration

Note: This is not the official copyright released version of the IEEE proceedings paper. When citing this paper, use the following format: Subramanian S, Cross M, Hirschhauser C, Johnson V, and Reistetter T, "Post-stroke upper limb rehabilitation using virtual reality interventions: Do outcome measures assess extent or type of motor improvement?", Proc. 13th Int'l Conf. on Virtual Rehab., WG Wright, S Subramanian, G Fluet, M Agmon, RM Proffitt, M Roberts (Eds), Tel Aviv, Israel, 21-24 July 2019.

[12, 13]. However, these measures focus mainly on task–completion. The movement patterns used to complete the task are not considered. Previous studies have shown that use of compensatory trunk displacement movements explains about 11% (in ARAT) [14] and 52% of the variance in FMA scores [15]. Thus, while the use of these measures quantifies the extent (i.e. how much) of motor improvement, they fail to consider the type (i.e. use of movement patterns).

Use of kinematic measurement can provide information on aspects of movement patterns (joint range of motion, trunk displacement, interjoint co-ordination) and motor performance (movement straightness, speed and precision) [16]. Movement pattern outcomes help in distinguishing between recovery and compensation at the behavioral level [16, 17]. Recovery refers to the reacquisition of pre-morbid pattern of joint movements and rotations used to UL task performance. Compensations can be further subdivided into adaptive and substitutive categories. Adaptive compensations entail use of different joint rotations enabling task completion using the same end effector. Substitutive compensations require the use of a different end effector to achieve the same task.

The use of kinematic motor performance measures as impairment level outcomes is being increasingly encouraged [10, 18]. However, motor performance can be improved using compensatory movement patterns [19, 20]. Thus, consideration of movement pattern outcomes provides a better picture of motor improvement. It can help qualitatively quantify UL motor improvement in response to different post-stroke interventions, including the use of VR.

Two previous studies [21, 22] have reviewed outcomes measures used in studies involving use of VR for post-stroke rehabilitation. These articles included the use of VR for both upper and lower limb rehabilitation and did not focus on movement quality outcomes. Given that post-stroke UL motor improvement continues to be sub-optimal, it is essential to identify the best outcomes to be used with task practice in virtual environments. This will help characterize all aspects of motor improvement (i.e. the extent and the type). In addition, it will be useful in synthesis of research findings using techniques such as meta-analyses. The objective of our study was to characterize the outcomes in studies involving VR interventions in terms of measuring the extent and type of UL motor improvement after a stroke.

II. Methods

A. Literarure review

A comprehensive search of studies published in English between 2000-2018 involving adults was conducted by MKC and CSH. Databases searched included Medline, ISI Web of Science and IEEE Xplore. A variety of combinations of MeSH terms and key words including; stroke, cerebrovascular accident, upper limb, rehabilitation, virtual reality, virtual rehabilitation, hemiparesis, arm, outcome, measures and assessments were used. Included articles addressed the effects of multiple sessions of an intervention involving a VR component. We excluded case studies, studies with very small sample sizes (<5 participants) study protocols and systematic reviews. If the preliminary study results were published as part of a conference proceeding and the full paper was subsequently published as a different journal article, we only considered results from the journal article.

B. Data Extraction

We initially extracted information regarding all the outcomes that were assessed in each retrieved article. Then, we grouped the extracted outcomes under appropriate categories of the ICF, based upon available guidelines [23-25]. Some outcomes had items that could be classified under more than one category of the ICF. These outcomes were placed in the category most commonly used in the literature. The outcomes were then classified as those measuring the extent or type of recovery, in reference to existing literature [16, 26].

III. Results

We obtained a total of 100 studies after excluding duplicate citations. The proportions of studies obtained from the different databases using outcomes across the three different ICF categories and contextual factors is provided in Fig. 1. While 93% of the studies employed measures evaluating impairment, limitations in activity performance were assessed in 85 studies. Contextual factors (including measures of quality of life, motivation and mood) were assessed in 13 studies. A total of 10 studies used participation outcomes. The number of studies with the names of the different outcomes used to assess the severity of motor impairment, activity limitations, participation restrictions and contextual factors are presented in Tables 1, 2 and 3 respectively.

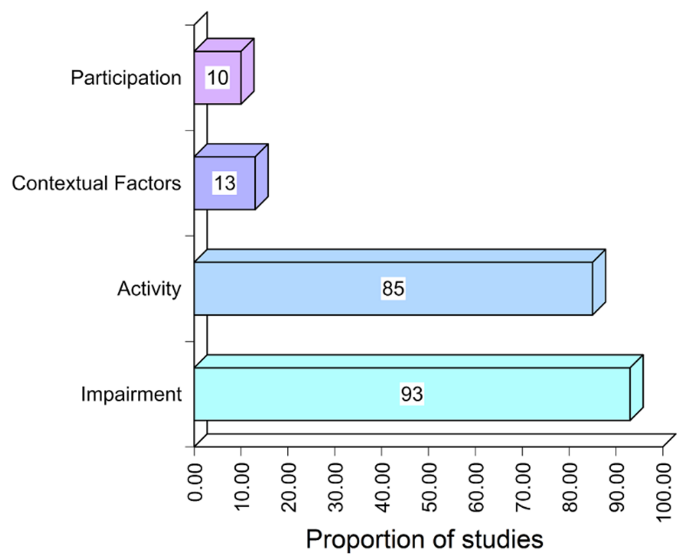

Fig 1: Distribution of proportions of studies using measures of impairment (teal), activity limitations (blue), contextual factors (lavender) and participation restrictions (purple). The numbers in the bars refer to the value.

A. Motor Impairment outcomes

Twenty different assessments were used across the 86 studies to assess the severity of motor impairment (Table 1). All the studies used ≥1 measure of impairment. Studies using ≥1 measure of impairment evaluated effects of the intervention on function and strength or spasticity as well as kinematic measures. The FMA was the most commonly employed outcome, being used in 59 studies. Motor performance kinematic measures were the second most commonly assessed type of outcome, being used in 40 studies. Manual Muscle testing, the Motricity Index, dynamometry as well as pinch and grip strength assessments quantified muscle strength. The joint ranges of motion were assessed using kinematic measurement as well as goniometry. Spasticity was assessed using the Original and Modified Ashworth's Scale. Additional outcomes used included use of fMRI, Motor Evoked Potentials (MEPs), Brunnstrom's stages and the Reaching Performance Scale in Stroke (RPSS).

TABLE 1. OUTCOMES USED TO MEASURE MOTOR IMPAIRMENT

Impairment level assessment	No. of studies
Fugl-Meyer Assessment	59
Motor performance kinematic measures (movement speed, error, straightness, smoothness)	40
Strength assessments	30
Movement pattern kinematic measures	13
Spasticity	7
fMRI outcomes	4
Changes in Motor Evoked Potential after TMS	4
Motor Function Test	3
Range of motion using goniometry	3
Reaching Performance Scale in Stroke	3
Maximal Forward Reach Distance (cm)	2
Brunnstrom's stages	1
Chedoke McMaster Stroke Assessment	1

B. *Activity Limitation outcomes*

Nine different outcomes were used to measure activity limitations (Table 2). The Wolf Motor Function Test (WMFT) was used most commonly in 35 studies. Hand manipulation and dexterity skills were assessed using 4 different outcomes including the Box and Blocks Test, the Nine Hole Peg Test, the Perdue Pegboard and the Grooved Pegboard Test in 32 studies. Other assessments used less frequently to measure limitations in ADL included the Action Research Arm Test and the Motor Activity Log (15 studies each), Jebsen-Taylor function test (12 studies), Functional Independence Measure (11 studies) the Barthel Index (including the Modified and the Korean Versions – 9 studies), the Chedoke Arm and Hand Activity Inventory (CAHAI – 6 studies). Assessments used in three or less studies included the ABILHAND, Functional tests of the Hemiparetic Upper Extremity, Assessment of Motor and Processing Skills, the Canadian Occupational Performance Measure, Fatigue Severity Scale and the Stroke Upper limb Capacity Scale.

TABLE 2. OUTCOMES USED TO MEASURE ACTIVITY LIMITATIONS

Activity level assessment	No. of studies
Wolf Motor Function Test	35
Hand function assessments	32
Action Research Arm Test	15
Motor Activity Log	15
Jebsen-Taylor Test	12
Functional Independence Measure	11
Barthel Index	9
Chedoke Arm and Hand Activity Inventory	6
ABILHAND	3
Nottingham Extended Activities of Daily Living	2
Functional Test of the Hemiparetic Upper Extremity	2
Assessment of Motor and Processing Skills	1
Canadian Occupational Performance Measure	1
Fatigue Severity Scale	1
Stroke Upper Limb Capacity Scale	1

C. *Participation Restriction and Contextual factor outcomes*

TABLE 3. OUTCOMES USED TO MEASURE PARTICIPATION RESTRICTION AND CONTEXTUAL FACTORS

Participation level and other assessments	No. of studies
Stroke Impact Scale	10
Intrinsic Motivation Inventory	7
Quality of Life measures	3
Depression assessments	3

The Stroke Impact Scale was the only outcome used to assess participation restriction in 10 studies. In terms of contextual factors, quality of life, motivation and the presence of depression were assessed (Table 3). The SF-36, Stroke Specific Quality of Life and EuroQol – 5D 3L outcomes helped assess quality of life. The Intrinsic Motivation Inventory was used to assess motivation. Depression was assessed using the

Beck's Depression Inventory and the Hamilton Depression Rating Scale.

D. Extent vs type of motor improvement

Outcomes that assessed the type of recovery were only used in 48 out of 100 studies. The proportion of studies that used outcomes assessing behavioral recovery and different types of compensations is given in Table 4. Amongst these 48 studies, 29 used outcomes (WMFT and CAHAI) that considered the presence of substitutive compensations while assigning a score. Nine studies used outcomes that assessed behavioral recovery (movement pattern kinematics) as well as accounted for the use of substitutive compensations (WMFT/CAHAI). Two studies used outcomes that evaluated both adaptive (Reaching Performance Scale in Stroke; RPSS) and substitutive (WMFT) compensations. Behavioral recovery using movement kinematics/ranges of motion were evaluated in seven studies. Only one study used movement kinematics and clinical outcomes that assessed the use of both adaptive (RPSS) and substitutive compensations (WMFT).

TABLE 4. OUTCOMES THAT MEASURE THE TYPE OF MOTOR IMPROVEMENT

Construct assessed	No. of studies
Substitutive Compensation only	29
Behavioral Recovery and Substitutive Compensation	9
Behavioral Recovery only	7
Substitutive and Adaptive Compensation	2
Behavioral Recovery, Substitutive and Adaptive Compensation	1

IV. DISCUSSION

Amongst studies using VR interventions for post-stroke UL motor improvement, we sought to characterize the outcomes in terms of measurement of extent or type of motor improvement. Initially, we initially classified the outcomes based upon the categories of the ICF. Our results indicate that more than 80% of all the studies we retrieved used outcomes assessing the severity of motor impairment and/or activity limitations. A smaller proportion of studies used outcomes assessing participation restrictions and/or effects of contextual factors.

A. ICF Categories

A total of 35 different outcomes were used across all the different ICF categories. All of outcomes have well-established psychometric properties [23-25]. Although quite variable, these numbers are lower than those reported previously [8, 9]. One of the reasons for the low numbers is that while previous reports have focused on the effects of a variety of interventions, our current study focused on the effects of only VR based interventions

Amongst the 20 different outcomes used to assess motor impairment, the FMA and motor performance kinematic measures were used most commonly. As previously mentioned, international consensus panels [11] recommend the use of these outcomes as measures of motor impairment. Thirty percent of the studies retrieved assessed muscle strength. The use of strength measures needs to be encouraged, especially as they are a quick and feasible assessment. In addition, muscle strength assessment can help make predictions about UL motor improvement capacity [27].

Although an exceedingly small proportion, it is interesting to note that studies are beginning to use outcomes indicative of change in neural pathways in response to VR interventions. Four studies each used fMRI to assess the extent of activation in ipsilesional areas and transcranial magnetic stimulation (TMS) to derive motor map measures and MEPs. Thus, there is a growing interest in the mechanisms of UL motor improvement facilitated using VR interventions. The presence or absence of MEPs on the more-affected side is an additional factor that helps predict the UL motor improvement capacity [27].

The WMFT was the most commonly used activity limitation measure, being used in little more than a third (35%) of all studies. In addition, other studies used UL specific outcomes such as the WMFT, ARAT, MAL and CAHAI. Previous reviews of outcome measures have suggested that these assessments may be most appropriate to assess severity of motor impairment and extent of activity limitations [28, 29]. Additional assessments used include more generic outcomes such as the FIM and Barthel's Index. The use of more generic outcomes might result in the possibility of the detection of no significant change on these measures.

The use of VR interventions generally involves task-specific practice of UL tasks to enhance motor improvement. For task completion, the nervous system to co-ordinate specific number of joints using the available motor abundance, within the given task-constraints [30]. Previous findings involving task-specific UL exercises have argued that even use of activity level measures such as the MAL may not truly reflect the change in inter-joint and inter-segmental co-ordination [31]. This is attributable to the fact that these outcomes include items involving movements requiring patterns of co-ordination vastly different from what the participants were trained in within virtual environments. Previous study results have demonstrated that task-specific changes are limited to the body-segment that is trained and do not translate to significant change in outcomes such as the Barthel's Index [5] and the FIM [32].This can be attributed to the fact that we might not be using the most-suitable measure. Thus, there is a need to judiciously select the outcome to ensure measurement and detection of appropriate change.

Our results also reveal studies are beginning to use outcomes assessing participation restrictions as well as the effect of contextual factors. The inclusion of participation and quality of life outcomes is a sign of progress, given that exclusion of these outcomes was a routine limitation in prior studies [20]. The inclusion of motivation and depression outcomes should also be encouraged, given that they tend to be confounding factors that can influence the delivery as well as effect of the intervention [31].

B. Type of motor improvement

Forty-eight studies used outcomes assessing the type of motor improvement. Majority of these studies used a measure where individuals scored lower if they used substitutive compensations. Only about a third of these studies (n = 17) used outcomes that assessed behavioral recovery. Behavioral recovery measures are usually obtained using kinematic analyses.

Kinematic assessment generally requires the use of specialized equipment, technical knowledge and may not be feasible in smaller clinics. If available, it is a resource that is highly desirable to use. The recent availability of low-cost devices such as the Kinect have increased the access to such sophisticated measurement. Initial studies reported significant measurement errors [33, 34] with use of the Kinect. However, this issue seems to have been resolved with use of software modifications and filtering parameters [35, 36]. Another viable option to obtain movement pattern kinematic outcomes is using inertial measurement units [37].

In terms of clinical outcomes, the Reaching Performance Scale in Stroke (RPSS) [38] is one of the few measures that assesses movement patterns. The RPSS is based upon observational kinematics [39], has well established psychometric properties [38, 40] and includes items that assess motor performance and movement patterns. It measures adaptive compensations, as the use of altered movement patterns entails a lower score. The RPSS represents a feasible clinical outcome that quantifies the type of recovery. In the absence of kinematic measurement, the use of the RPSS has been suggested as a suitable alternative outcome [16].

V. Conclusion

Majority of the studies that use VR to enhance post-stroke UL rehabilitation use outcomes that assess the extent of motor improvement. However, the proportion of studies using outcomes that assess the type of recovery is steadily increasing. We found that the FMA, WMFT and SIS are the most commonly used outcomes the impairment, activity limitation and participation restriction levels respectively. In addition to the outcomes mentioned above, the inclusion of movement pattern as kinematic well as motor performance outcomes (if available) or RPSS will provide additional information on the type of recovery. The use of more than one outcome is suggested to capture all facets of motor improvement [26, 41].

VI. References

[1] V. L. Feigin, R. V. Krishnamurthi, P. Parmar, B. Norrving, G. A. Mensah, D. A. Bennett*, et al.*, "Update on the global burden of ischemic and hemorrhagic stroke in 1990-2013: The GBD 2013 study," *Neuroepidemiology,* vol. 45, pp. 161-76, 2015.

[2] I. Faria-Fortini, S. M. Michaelsen, J. G. Cassiano, and L. F. Teixeira-Salmela, "Upper extremity function in stroke subjects: relationships between the international classification of functioning, disability, and health domains," J *Hand Ther.* vol. 24, pp. 257-265, 2011.

[3] G. Kwakkel, B. J. Kollen, and J. W. Krakauer, "Predicting activities after stroke," in *Textbook of Neural Repair and Rehabilitation*. M. E. Selzer, S. Clarke, L. G. Cohen, G. Kwakkel and R. H. Miller , Eds., 2nd ed Cornwall, UK: Cambridge University Press, 2014, pp. 585-600.

[4] D. Hebert, M. P. Lindsay, A. McIntyre, A. Kirton, P. G. Rumney, S. Bagg*, et al.*, "Canadian stroke best practice recommendations: stroke rehabilitation practice guidelines, update 2015," *Int J Stroke,* vol. 11, pp. 459-484, 2016.

[5] S. K. Subramanian and S. S. Prasanna, "Virtual reality and noninvasive brain stimulation in Stroke: how effective is their combination for upper limb motor improvement? - A meta-analysis," *PM & R,* vol. 10, pp. 1261-1270, Nov 2018.

[6] World Health Organization, "Comprehensive ICF core set for stroke," *Nottwill, ICF Research Branch,* 2013.

[7] K. Salter, N. Campbell, M. Richardson, S. Mehta, J. Jutai, N. Zettler; et al Outcome Measures in Stroke Rehabilitation [Online]. Available: http://ebrsr.com/evidence-review/20-outcome-measures-stroke-rehabilitation; accessed Jan 15, 2019.

[8] J. M. Veerbeek, G. Kwakkel, E. E. van Wegen, J. C. Ket, and M. W. Heymans, "Early prediction of outcome of activities of daily living after stroke: a systematic review," *Stroke,* vol. 42, pp. 1482-8, May 2011.

[9] M. Ali, C. English, J. Bernhardt, K. S. Sunnerhagen, M. Brady, and V. I.-R. Collaboration, "More outcomes than trials: a call for consistent data collection across stroke rehabilitation trials," *Intl J Stroke,* vol. 8, pp. 18-24, Jan 2013.

[10] J. Salinas, S. M. Sprinkhuizen, T. Ackerson, J. Bernhardt, C. Davie, M. G. George*, et al.*, "An International Standard Set of Patient-Centered Outcome Measures After Stroke," *Stroke,* vol. 47, pp. 180-6, Jan 2016.

[11] G. Kwakkel, N. A. Lannin, K. Borschmann, C. English, M. Ali, L. Churilov*, et al.*, "Standardized measurement of sensorimotor recovery in stroke trials: Consensus-based core recommendations from the Stroke Recovery and Rehabilitation Roundtable," *Int J Stroke,* vol. 12, pp. 451-461, Jul 2017.

[12] N. Yozbatiran, L. Der-Yeghiaian, and S. C. Cramer, "A standardized approach to performing the action research arm test," *Neurorehabil Neural Repair,* vol. 22, pp. 78-90, 2008.

[13] J. See, L. Dodakian, C. Chou, V. Chan, A. McKenzie, D. J. Reinkensmeyer*, et al.*, "A standardized approach to the Fugl-Meyer assessment and its implications for clinical trials," *Neurorehabil Neural Repair,* vol. 27, pp. 732-741, 2013.

[14] M. Alt Murphy, C. Willen, and K. S. Sunnerhagen, "Movement kinematics during a drinking task are associated with the activity capacity level after stroke," *Neurorehabil Neural Repair,* vol. 26, pp. 1106-15, Nov-Dec 2012.

[15] S. K. Subramanian, J. Yamanaka, G. Chilingaryan, and M. F. Levin, "Validity of movement pattern kinematics as measures of arm motor impairment poststroke," *Stroke,* vol. 41, pp. 2303-8, Oct 2010.

[16] M. F. Levin, J. A. Kleim, and S. L. Wolf, "What do motor "recovery" and "compensation" mean in patients following stroke?," *Neurorehabil Neural Repair,* vol. 23, pp. 313-9, May 2009.

[17] J. A. Kleim, "Neural plasticity and neurorehabilitation: teaching the new brain old tricks," *J Commun Disord,* vol. 44, pp. 521-8, Sep-Oct 2011.

[18] J. W. Krakauer and J. C. Cortes, "A non-task-oriented approach based on high-dose playful movement exploration for rehabilitation of the upper limb early after stroke: A proposal," *NeuroRehabilitation,* vol. 43, pp. 31-40, 2018.

[19] S. M. Michaelsen, R. Dannenbaum, and M. F. Levin, "Task-specific training with trunk restraint on arm recovery in stroke: randomized control trial," *Stroke,* vol. 37, pp. 186-92, Jan 2006.

[20] S. K. Subramanian, C. B. Lourenco, G. Chilingaryan, H. Sveistrup, and M. F. Levin, "Arm motor recovery using a virtual reality intervention in chronic stroke: randomized control trial," *Neurorehabil Neural Repair,* vol. 27, pp. 13-23, Jan 2013.

[21] G. C. Palma, T. B. Freitas, G. M. G. Bonuzzi, M. A. A. Soares, P. H. W. Leite, N. A. Mazzini*, et al.*, "Effects of virtual reality for stroke individuals based on the International Classification of Functioning and Health: a systematic review," *Top Stroke Rehabil,* vol. 24, pp. 269-278, 2017.

[22] M. Veras, D. Kairy, M. Rogante, C. Giacomozzi, and S. Saraiva, "Scoping review of outcome measures used in telerehabilitation and virtual reality for post-stroke rehabilitation," *J Telemed Telecare,* vol. 23, pp. 567-587, 2017.

[23] Shirley Ryan Ability lab. Rehabilitation Measures Database [Online]. Available: https://www.sralab.org/rehabilitation-measures; accessed January 15, 2019

[24] Heart and Stroke Foundation Canadian Partnership for Stroke Recovery. Stroke Engine Assessments [Online]. Available: www.strokengine.ca/assess, accessed January 20, 2019.

[25] J. E. Sullivan, B. E. Crowner, P. M. Kluding, D. Nichols, D. K. Rose, R. Yoshida*, et al.*, "Outcome measures for individuals with stroke: process and recommendations from the American Physical Therapy Association neurology section task force," *Phys Ther,* vol. 93, pp. 1383-96, Oct 2013.

[26] M. Demers and M. F. Levin, "Do activity level outcome measures commonly used in neurological practice assess upper-limb movement quality?," *Neurorehabil Neural Repair,* vol. 31, pp. 623-637, Jul 2017.

[27] C. M. Stinear, "Prediction of motor recovery after stroke: advances in biomarkers," *Lancet Neurol,* vol. 16, pp. 826-836, Oct 2017.

[28] M. Alt Murphy, C. Resteghini, P. Feys, and I. Lamers, "An overview of systematic reviews on upper extremity outcome measures after stroke," *BMC Neurol,* vol. 15, p. 29, Mar 11 2015.

[29] L. Santisteban, M. Teremetz, J. P. Bleton, J. C. Baron, M. A. Maier, and P. G. Lindberg, "Upper limb outcome measures used in stroke rehabilitation studies: A systematic literature review," *PLoS One,* vol. 11, p. e0154792, 2016.

[30] S. L. Gorniak,V. M. Zatsiorsky, and M. L. Latash, "Manipulation of a fragile object. *Exp Brain Res,* vol. 202, pp. 413-430, April 2010.

[31] S. K. Subramanian, G. Chilingaryan, H. Sveistrup, and M. F. Levin, "Depressive symptoms influence use of feedback for motor learning and recovery in chronic stroke," *Restor Neurol Neurosci,* vol. 33, pp. 727-40, 2015.

[32] J. Higgins, N. M. Salbach, S. Wood-Dauphinee, C. L. Richards, R. Cote, and N. E. Mayo, "The effect of a task-oriented intervention on arm function in people with stroke: a randomized controlled trial," *Clin Rehabil,* vol. 20, pp. 296-310, Apr 2006.

[33] G. Tao, P. S. Archambault, and M. Levin, "Evaluation of Kinect skeletal tracking in a virtual reality rehabilitation system for upper limb hemiparesis," in *Proceedings of 2013 International Conference on Virtual Rehabilitation (ICVR),* 2013, pp. 164-165.

[34] M. Huber, M. Leeser, D. Sternad, and A. L. Seitz, "Accuracy of kinect for measuring shoulder joint angles in multiple planes of motion," in *Proceedings of the 2015 International Conference on Virtual Rehabilitation (ICVR),* 2015, pp. 170-171..

[35] R. J. Adams, M. D. Lichter, E. T. Krepkovich, A. Ellington, M. White, and P. T. Diamond, "Assessing upper extremity motor function in practice of virtual activities of daily living," IEEE *Trans Neural Sys Rehabil Eng* vol. 23, pp. 287-96, Mar 2015

[36] S. S. Esfahlani, B. Muresan, A. Sanaei, and G. Wilson, "Validity of the Kinect and Myo armband in a serious game for assessing upper limb movement," *Entertain Comput.,* vol. 27, pp. 150-156, 2018.

[37] D. Perez-Marcos, O. Chevalley, T. Schmidlin, G. Garipelli, A. Serino, P. Vuadens*, et al.*, "Increasing upper limb training intensity in chronic stroke using embodied virtual reality: a pilot study," *J Neuroeng Rehabil,* vol. 14, p. 119, Nov 17 2017.

[38] M . F. Levin, J. Desrosiers, D. Beauchemin, N. Bergeron, and A. Rochette, "Development and validation of a scale for rating motor compensations used for reaching in patients with hemiparesis: the reaching performance scale," *Phys Ther,* vol. 84, pp. 8-22, Jan 2004.

[39] J. Bernhardt, P. J. Bate, and T. A. Matyas, "Accuracy of observational kinematic assessment of upper-limb movements," *Phys Ther,* vol. 78, pp. 259-70, Mar 1998.

[40] S. K. Subramanian, M. C. Banina, G. Chilingaryan, G.; M. F. Levin, "Reaching Performance Scale for stroke: test-retest reliability and concurrent and discriminant validity in individuals with chronic stroke", presented at the World Congress of Neurological Rehabilitation, Philadelphia, PA, 2016.

[41] E . Bagiella, "Clinical trials in rehabilitation: single or multiple outcomes?," *Arch Phys Med Rehabil,* vol. 90, pp. S17-21, Nov 2009.