Development and validation of tele-health system for stroke rehabilitation

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ABSTRACT

Tele-rehabilitation refers to the use of information and communication technologies to provide rehabilitation services to people in their homes or other environments. The objective of this paper is to present the development, validation and usability testing of a low-cost, markerless full body tracking virtual reality system designed to provide remote rehabilitation of the upper extremity in patients who have had a stroke. The Methods and Results sections present the progress of our work on system development, system validations and a feasibility/usability study. We conclude with a brief summary of the initial stages of an intervention study and a discussion of our findings in the context of the next steps. The validation study demonstrated considerable accuracy for some outcomes (i.e., shoulder “pitch” angle, elbow flexion, trunk forward and side-to-side deviation). In addition positive responses were received from the clients who participated in the feasibility study. We are currently at the process of improving the accuracy of the system as well as conducting a randomized clinical trial to assess the effectiveness of the system to improve upper extremity function post-stroke.

1. INTRODUCTION

Tele-rehabilitation refers to the use of information and communication technologies to provide rehabilitation services to people in their homes or other environments (Burdea et al., 2000). The goal is to improve patient access to care by providing therapy beyond the physical walls of a traditional healthcare facility, thus expanding continuity of care to persons with disabling conditions. The need for evolving the delivery of rehabilitation services and incorporating aspects of self-care and remote monitoring is important in light of the shift in global demographics to an older population and the increasing prevalence of chronic health conditions (Bowling, 2007). Tele-rehabilitation holds significant potential to meet this need and to provide services that are more accessible to more people, while having the ability to offer a more affordable and available care. Moreover, research in neuroscience and especially brain plasticity emphasizes the need for intense treatment and rehabilitation following the acute phase and continuing when the person returns home (Winstein et al., 1999).

The recent development of advanced sensor and remote monitoring technologies has enabled an increasing number of tele-rehabilitation applications to be deployed in the home (e.g., Deutsch et al., 2007; Kairy et al., 2009; Bendizen et al., 2009; Durfee et al., 2009; Golomb et al., 2009; McCue et al., 2010; Mountain et al., 2010). While early telecare projects looked to provide basic follow-up services and caregiver support, later work developed and deployed systems to provide home-based exercise monitoring, diet and medication compliance tracking, robotic-based treatment, and other more dynamic interventions. The advent of low-cost, markerless full body tracking technologies (Microsoft, 2011) has given impetus to continued development and evaluation of robust systems for home use. Research is currently focusing on development of games suitable for use by adults and the elderly with physical and cognitive impairment

(Lange et al., 2009) and on validation of virtual marker identification using customized and commercial tools (Schönauer et al., 2011; Suma et al., 2011; Lange et al., 2011).

The objective of this paper is to present the development, validation and usability testing of a low-cost, markerless full body tracking virtual reality system designed to provide remote rehabilitation of the upper extremity in patients who have had a stroke. The Methods and Results sections present the progress of our work on system development, system validations and a feasibility/usability study. We conclude with a brief summary of the initial stages of an intervention study and a discussion of our findings in the context of the next steps.

2. DESCRIPTION OF GERTNER TELE-MOTION-REHAB SYSTEM

The Gertner Tele-Motion-Rehab system has been designed to provide a home-based tele-rehabilitation program to improve the motor and functional status of people who have neurological dysfunction such as stroke. The set-up includes interaction between the remote client (currently in an on-site lab that simulates the person's home) and the central, hospital-based clinician. The central system includes a unit to support all software to monitor the activity of the remote client and facilities for electronic data storage of intervention outcomes. We use a 3D video capture camera based system (Kinect camera and Microsoft Kinect Software Developer's Kit (SDK)) in which the client's gesture motions control the action of the games. As illustrated schematically in Fig. 1, the system is configured to ensure that it will be a viable online (one-to-one) or asynchronous (one clinician-to-multiple clients) alternative for the rehabilitation of motor and cognitive impairment in patients with neurological dysfunction.

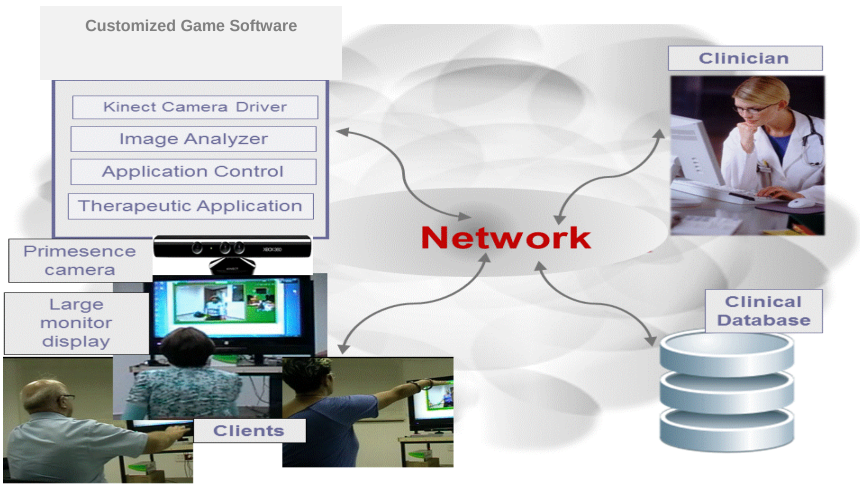

Figure 1. *Schematic illustration of the Tele-Motion-Rehab system as configured for remote, online interaction between client and clinician and/or offline monitoring by the clinician of one or more clients.*

2.1 Design principles of Gertner Tele-Motion-Rehab system.

The software was designed to include both assessment and game-like functional intervention activities. The following design principles were incorporated.

- *Control over level of difficulty.* The level of difficulty is adjusted to the client's abilities (motor and cognitive) to provide just the right challenge of activities/tasks.
- *Knowledge of results.* On-going feedback of game results are provided online to the client as the game progresses and as summary scores at the end of each game. (Details of these scores are provided below in Table 1) These results are also stored off-line for ongoing review by the clinician and retrieval for the client in subsequent sessions.
- *Knowledge of performance.* Ongoing feedback of the quality of movements of the upper limbs as well as compensatory movements of the trunk are provided online (details of this feedback are provided in the next section). This feedback is controlled by a clinician at the evaluation phase in order to match the extent of feedback given to the client's abilities.

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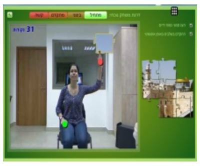
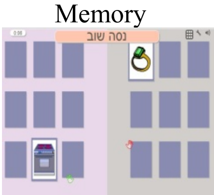
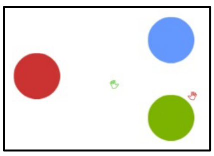
2.2 Evaluation Software

A full kinematic evaluation program was created in order to assess the client's range of motion of the shoulder (flexion and abduction) and elbow (flexion) as well as the magnitude of compensations that occurred while making these movements (shoulder elevation, elbow flexion and trunk lateral and anterior-posterior motion). These data are saved and used to establish the parameters for all games and tasks; when necessary (e.g., the client was fatigued on a given day), the parameters may be adjusted remotely by the clinician. However, they only reset for the games and tasks following a subsequent running of the evaluation program. The re-evaluation program is rerun after a series of four intervention sessions.

Table 1. *Description of five Tele-Motion-Rehab games and tasks developed to date.*

			Level of Difficulty	
Game/Task	Description	Scoring	Motor	Cognitive
Puzzle 	Client reaches to touch puzzle pieces as they appear on the screen. Pieces are automatically placed in correct location when touched. Level of difficulty is changed by pieces appearing at more distant shoulder Range of Motion and by successively requiring that client dwell on one or two pieces (not just touch them).	Time to complete each puzzle.	Simple	Simple
Memory 	Classic 'memory' game in in which cards on each side of the board are exposed until a match is found. Client selects cards by touching them. Level of difficulty is changed by changing display height and successively displaying more card pairs (4-16).	Time to complete game. Number of card selections to complete game.	Simple to difficult	Simple to moderate
Pizza/Hamburger 	Client responds to fast-food orders (pizza or hamburgers) from customers in accordance with a displayed menu. Selection of food items is by touch. The level of difficulty may be adjusted by changing the shelf height, by number of customers and by setting time to complete the meal to be longer. The completed meal is dragged to the customer.	Number of satisfied customers. Time to complete meals.	Moderate	Moderate
Arrows 	Client successively touches colored arrows causes them to move in the indicated direction until they reach "home". Moves have to be strategically planned such that an arrow of one color is used to move an arrow of the other color when necessary since arrows may not be moved backwards.	Number of moves used to complete game. Time to complete game.	Moderate to difficult	Moderate to complex
Tasks 	A series of tasks of increasing cognitive difficulty are solved by touching the indicated images in accordance with instructions (e.g., touch the blue circle first, then the green circle and then the red circle; touch the glasses of wine in order from most full to least full).	Highest level of difficulty achieved with least number of repetitions.	Moderate to difficult	Moderate to Complex

2.3 Customized games

To date, five Tele-Motion-Rehab games/tasks have been developed. As shown in Table 1, they differ in the type of motion required by the client as well as in their level of motor and cognitive difficulty. For all games several output files are generated and stored for subsequent analysis and review; these include raw kinematic marker data of movements, the parameters used to run the games for each client at each session and the variables describing the game scores.

A screenshot of the Hamburger short order cook task, as an example of one of the games, is shown in Fig. 2. The client plays the role of a short order cook, using gestures to select buns, burgers, tomatoes and ketchup in accordance with the customer's menu selection (shown on the right side of the screen). Both motor and cognitive requirements may be adjusted by changing, for example, the number of the items in the menu, the location of the food items (raising or lowering the shelves), preparation time and number of customers to be served. Note that a silhouette displaying the 3D location of client's head, trunk and shoulders is displayed on the lower right part of the screen; the silhouette's color and slant directly show the client's body position. In addition, visual and auditory messages are given when the client makes compensatory movements beyond a preset tolerance.

Figure 2. *Screenshot showing the Hamburger short order cook task. The client's order is specified in the conversation balloon and the ingredients are listed to the right of the screen. The top shelf is adjustable to make selections harder or easier.*

3. SYSTEM VALIDATION

Demonstration of the accuracy and validity of any low-cost video capture rehabilitation system is essential if it is to be used to provide independent performance (kinematic) feedback to clients. We conducted an extensive series of tests over the past two years at the CAREN™ Virtual Reality Lab, the Laboratory for Human Performance, at the Rehabilitation Center, Sheba Medical Center, Israel. The Vicon optokinetic system (www.vicon.com), consisting of 12 Vicon infra-red cameras and having a resolution of 2 mega pixels was used. Forty-one passive markers were placed on anatomical landmarks (Vicon Full Body protocol), and sampled at a frequency rate of 120 Hz. A healthy male, aged 42, was seated on a stool, and repeated each of the designated movements three times consecutively. A set of 21 movements, each repeated three times, replicating those required to operate the Tele-Motion-Rehab system, was used for each capture session. These movements included, for example, pure shoulder flexion, shoulder abduction and elbow flexion, followed by the same movements but with a concurrent compensation movement (e.g., shoulder elevation, elbow flexion, trunk lateral deviation).

For the purpose of this analysis, and subsequent use in the Tele-Motion-Rehab system, pure shoulder flexion is described as rotation around the x axis, or "pitch". If the movement is not a pure flexion movement, i.e., it includes some shoulder abduction, then the description of the movement is "ɵ" degrees of "pitch" with "ϕ" degrees of "yaw" (rotation around the y axis). The axes of rotation relative to the body are shown in Fig. 3. Outcome measures were computed from marker data (Vicon) and virtual marker data (Kinect), using custom-written Matlab programs (Math-works, Inc., Natick, MA, USA). A 95% limits of agreement method was used to evaluate differences between measurements, corrected for repeated measurements (Bland & Altman, 1986). In Table 2, 95% limits of agreement for each outcome measure and the mean standard deviation of the three repetitions of each movement are reported. Note that movements where shoulder "pitch" exceeds 115 degrees were removed from the calculation of shoulder elevation due to difficulty in identifying shoulder position (4 out of 21 movements were removed). Note also that negative values of the Bias measure indicate an undershoot of movement as identified via Kinect as compared to Vicon and a positive value denotes an overshoot.

Table 2. *95% limits of agreement for each outcome measure and the mean standard deviation of the three repetitions of each movement.*

	Bias (mean difference between measurements)	Limits of agreement (mean ± 1.96 SD)	SD between repetitions - Vicon	SD between repetitions - Kinect
Shoulder elevation (cm)	-1.25	[-5.23 2.74]	0.56±0.36	1.03±1.10
Trunk flexion/extension (cm)	-0.29	[-2.48 1.91]	1.06±0.79	0.98±0.75
Trunk side flexion (cm)	-0.68	[-3.48 2.12]	0.93±1.14	1.02±0.78
Pitch ROM (deg)	12.54	[2.23 22.85]	2.81±1.56	2.98±1.43
Yaw ROM (deg)	-1.06	[-33.29 31.17]	8.39±4.52	9.13±4.74
Elbow flexion ROM (deg)	-1.79	[-16.20 12.62]	2.95±2.19	4.65±4.31

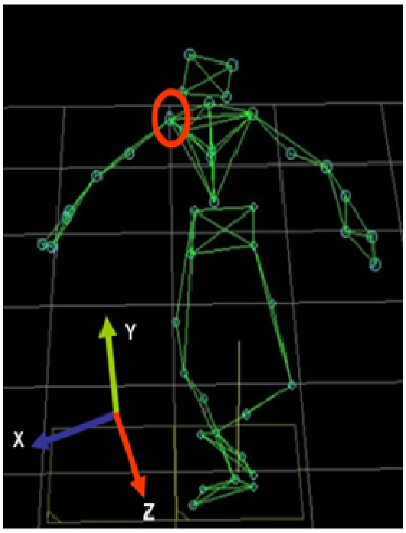


Figure 3. S*ubject model from Vicon marker set showing* x-y-z *axes of rotation relative to body.*

Kinect outcome data contain a small systematic bias for shoulder elevation, trunk flexion/extension and trunk lateral flexion ROM. For shoulder elevation, this bias may increase when shoulder elevation is larger. In all three cases, 95% of the differences are expects to lie under 4cm of the mean. The shoulder pitch angle contains a bias (overshoot of shoulder pitch in Kinect), but 95% of differences are expected within 10.3º of the mean. For all measurements, the between-repetitions SD is comparable to that obtained in Vicon (Table 2). In summary, use of these measures can be made while taking into account these limitations. One measure, the shoulder "yaw" angle had larger differences between measures (95% of differences expected within 32.2º of the mean). We also saw that this angle strongly depends on the subject's location in the workspace, due to nonlinearities in the Kinect workspace. This measure is, therefore, not yet accurate enough for independent use in a rehabilitation setting. Increases in the range of recorded movements as well as the addition of more repetitions of each movement should improve the reliability of our calculations.

Figure 4 shows plots of the outcome measures calculated from the Vicon (x-axis) versus the Kinect (y-axis). Each data point represents an average value of ROM values in three repetitions of the same movement. Dashed line represents the identity line. It is evident that the Kinect shoulder "pitch" angle, elbow flexion, trunk side flexion and trunk forward flexion are more accurate than the values for the shoulder "yaw" angle and shoulder elevation.

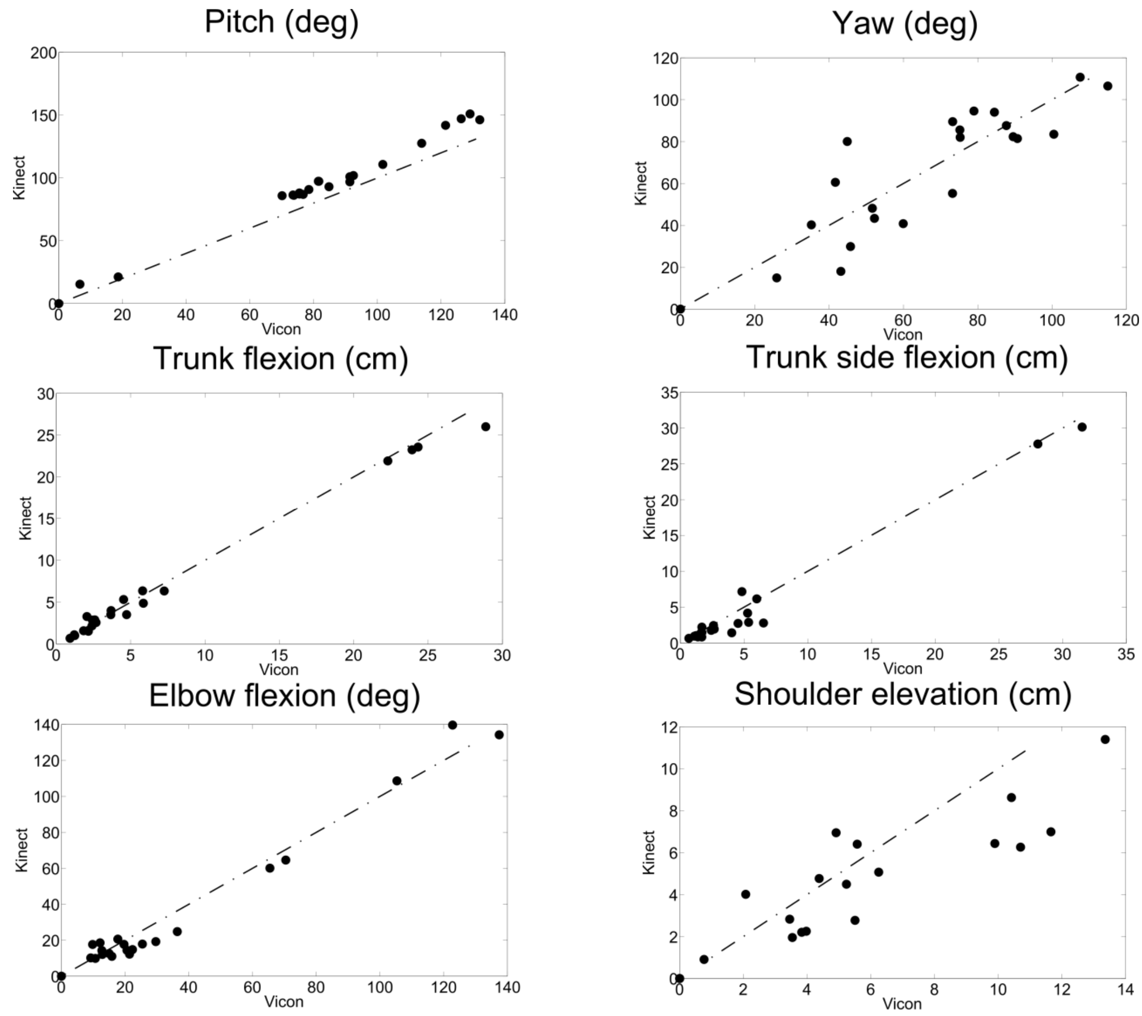


Figure 4: *Outcome measures calculated from Vicon (x-axis) and Kinect (y-axis) data. Each data point represents an average value of ROM values in 3 repetitions of the same movement. Dashed line represents the identity line.*

4. USABILITY STUDY

4.1 Methods

Eight clients with stroke (5 male, 3 female), aged 55-77 years (mean ± SD = 65.6 ± 8.0), participated in the study. Inclusion criteria included mild to moderate impairment of the affected upper extremity. Exclusion criteria included other medical conditions of the central or peripheral nervous system limiting participation in low-intensity exercise training; major receptive aphasia or inability to follow 2-stage commands and screening criteria consistent with dementia (Mini-Mental State Exam (MMSE) score <24); untreated major depression; presence of unilateral spatial neglect as determined by star cancellation (score less than 51); hemianopsia; limb and ideomotor apraxia. Their Fugl-Meyer Assessment for the upper extremity scores ranged from 35-54 (mean ± SD = 46.3 ± 6.5) and their MMSE scores ranged from 25-30 (mean ± SD = 27.6 ± 1.8).

Each subject participated in 6-7 one hour sessions in a hospital-based mock-up "tele" setting. The first sessions were used to assess motor, cognitive and functional abilities using standard clinical tests and then engaged in three sessions requiring upper extremity reaching motions while playing the games as described above. Outcomes included participant responses to the 5-point Short Feedback Questionnaire (SFQ) (Kizony et al., 2006), a usability questionnaire documenting their enjoyment, and perception of success and control while using the system. They also completed the Borg scale (1990) to rate their perceived effort while playing the games, where 6 indicates a minimal effort and 20 indicates a maximal effort. In addition to these subjective ratings, game performance scores were tabulated.

4.2 Results

Feedback from this study was very positive in terms of enjoyment (mean ± SD SFQ item 1 = 4.6 ± 0.52). The mean ± SD Borg scores = 9.9 ± 2.4 indicating a moderate rating of effort. The variability of the performance scores was considerably higher. For example, although shelf height and number of customers (n=5) served during the Hamburger short order cook task was the same for all participants, the time they took to complete it varied from 2.42-6.00 min (mean ± SD = 4.18 ± 1.29).

In the Memory game, the highest successfully completed level varied from a total of 4 pairs of matched cards (1 participant), to 6 pairs of matched cards (6 participants) and to 9 pairs of matched cards (1 participant). Time to complete the game ranged from 2.3-8.9 min (mean ± SD = 3.74 ± 2.19). However, when the number of cards per minute was calculated the variability decreased considerably (range = 1.0-2.6 cards per min; mean ± SD = 1.88 ± 0.62).

These results were used to determine the protocol for the clinical effectiveness study (via a small sample Randomized Control Trial) that we are now commencing and the optimal way to provide feedback when clinician and client are not in face-to-face contact.

5. CONCLUSIONS

The results of this study indicated that the 'Gertner Tele Rehab system' is feasible for use for upper extremity rehabilitation after stroke. The validation study has, to date, demonstrated considerable accuracy for some outcomes (i.e., shoulder “pitch” angle, elbow flexion, trunk forward and side-to-side deviation). The accuracy of other outcomes, namely shoulder “yaw” and should elevation need to be improved before they can be used to provide online clinical feedback. We are currently continuing to improve system accuracy and, in the meantime, use the problematic outcomes with great caution.

Several modifications to the software were made as a result of the feasibility study, and prior to commencement of the ongoing Randomized Control Trial (RCT). For example, small demonstration applications were made to instruct the clients regarding the movements required to control each game. Additional games that include a greater cognitive challenge which makes them more similar to tasks encountered in real life settings were developed. The games were adjusted to better accommodate both motor and cognitive abilities of the clients. Preliminary results from the RCT in which a 12-session tele-intervention is being compared to self-directed home exercises, indicate that the revised system is feasible and enjoyable. These results will be presented at the conference.

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