A simple camera tracking virtual reality system for evaluation of wrist range of motion

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ABSTRACT

Clinicians assess wrist and hand function to identify pathology, monitor effectiveness of treatment, and determine the readiness to return to work and other activities. The goniometer, the conventional evaluation tool used to assess range of motion (ROM), is most suited to the measurement of passive and active joint ROM under conditions that entail static, non-functional movements. Instruments that measure ROM during complex, dynamic tasks may encumber the movement. We have adapted a simple optical tracking device that uses a low-cost webcam to track two diodes, referred to as the Virtual Wrist Tracker (VWT), to assess wrist ROM in 30 subjects, aged 18-65 years; fifteen patients had sustained orthopaedic injuries and 15 were control subjects. ROM was assessed by a standard goniometer and by the VWT under two conditions: visual auditory feedback and auditory pacing feedback. The results of test-retest analysis of control subjects demonstrated good reliability for the VWT during wrist extension and moderate reliability during wrist flexion. High, significant correlations were found between the ROM for wrist extension and flexion as measured by a goniometer and via the VWT in the research group and for wrist extension but not for wrist flexion in the control group. A repeated measures ANOVA mixed design showed no significant differences in wrist extension ROM or in wrist flexion ROM during the performance of the task with visual and auditory feedback versus a task with auditory pacing, nor was there interaction effects between task type and group during extension and flexion. Wrist ROM in either direction increased as the participant progressed from one target rectangle to the next; statistically significant interaction effect was found between ROM in target position and group indicating that the difference between the targets in the control group was significantly different than in the research group. Finally, both groups enjoyed performing the VWT tasks but the control subjects felt greater presence, success and control. The VWT appears to be a reliable and valid tool for assessing wrist ROM during dynamic activities.

1. INTRODUCTION

The wrist is a complex joint which includes a large group of tendons, nerves and blood vessels that enable various movements to occur when performing a task. There are many orthopedic pathologies that can occur in the wrist, the most common of which is a fracture of the distal radius (MacDermid et al., 2003; Larsen & Lauritsen, 1993). Clinicians assess wrist and hand function in order to identify pathology, to monitor the effectiveness of treatment, to determine the readiness to return to work and other daily activities, and to evaluate their permanent partial incapacity in order to help determine eventual financial compensation and/or need for vocational retraining (Fess, 1986; Schulz-Johnson, 1987; Swanson et al., 1983; Dipietro et al., 2003). This evaluation includes measures of range of motion, strength and sensation as well as observations related to the loss of limbs, hypersensitivity and cosmesis. Achievement of these clinical goals is confounded

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by the questionable reliability and validity of some of the clinical measures as well as their limitations as dynamic kinematic tools (Weiss et al., 1994).

The goniometer, a metal or plastic protractor-like instrument, is the conventional evaluation tool used to measure range of motion (ROM) of the injured wrist. Specific guidelines, developed by the American Academy of Orthopedic Surgeons and the American Society of Hand Therapists, have identified the required placement of the goniometer as well as the correct position of the upper extremity during ROM measurements. Provided that these guidelines are followed, most researchers agree that goniometric measures of joint range of motion are valid and reliable (Hamilton and Lachenbruch, 1969; Stratford et al., 1984; Gadjdosk and Bohannon, 1987).

Goniometry is most suited to the measurement of passive and active joint range of motion under conditions that entail static, non-functional movements. These are clearly important limitations since the upper extremity engages primarily in complex, dynamic tasks. Moreover, patients, aware of the significance of the hand and wrist assessment, may generate less than their actual active range of motion thereby protracting the time spent in therapy, the days away from work and the cost in compensation.

Over the years a number of alternate methods have been proposed to replace the goniometer for the measurement of wrist range of motion. These include electrogoniometers (Rawes et al., 1996), exoskeleton type apparatus, and glove-based devices (Dipietro et al., 2003). These methods overcome the limitation of static ROM measures but have other drawbacks including encumbrance and difficulty in aligning the sensor to the joint axis (Weiss et al., 1994). An alternate class of instruments is marker-based video tracking (Rab et al., 2002; van Andel, 2008) which do not encumber the subject's limb and are usually more accurate in identifying axes of rotation (Moeslund et al., 2006).

There is a need for tools that measure functional activity and participation as well as support interventions that motivate patients to engage in repetitive practice. The aim is to assess an individual's functional ability in a natural context which takes into account environmental demands while implementing dynamic assessment of hand and wrist function. Virtual reality (VR) is a natural choice as a means of achieving all these aims while supporting an accurate and reliable evaluation of performance similar to the real world (Rizzo and Kim, 2005). In addition, VR technology can improve the consistency and relevance of assessment to the individual's daily life. Given the financial and technical constraints in most clinical settings, the use of simple, low-cost VR technologies is desirable.

A simple, camera tracking VR system was developed by Yeh and Rizzo from the Institute of Creative Technologies at the University of Southern California (Yeh et al., 2008). It is an optical tracking device that utilizes low-cost dual webcams to track with two diodes providing information of six degrees of freedom with a sampling rate of 60 Hz. In the current study, a single camera was used to evaluate planar motion. The participants grasp the hand-held LED, shown in Fig. 1, while viewing the vertical and horizontal motion of a virtual airplane. The task is to steer the airplane through rectangular frames of various sizes and heights in the virtual environment. In order to perform this task, the participants were asked to grasp the grey part of the LED unit with their fingers and flex and extend their wrists. The system provides information regarding the number of successful tracking motions and the motion of the optical device i.e., flexion and extension of the wrist in space.

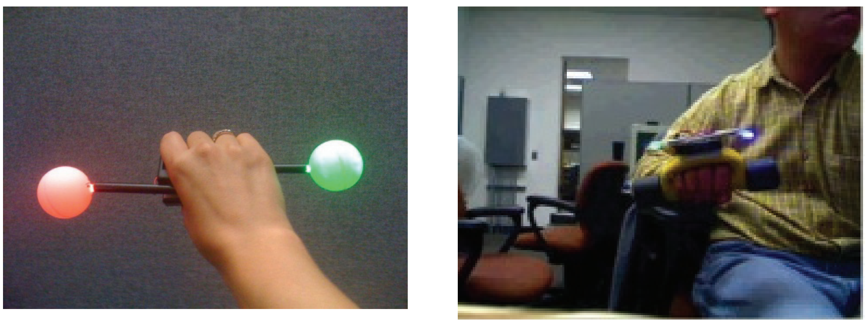

Figure 1. *An optical tracking device that utilizes one or two low-cost webcams to track one, two or three diodes providing information of three, five, or six degrees of freedom, developed by Yeh et al. (2008).*

An initial study of the optical tracking device compared its utility relative to Ascension's Flock of Birds (*http://www.ascension-tech.com/realtime/RTflockofBIRDS.php*) six degrees-of-freedom magnetic tracking system (Yeh et al., 2008). Both the optical and magnetic tracking devices scored highly in the user perception questionnaire and the optical tracker performed as well as magnetic tracking system for game tasks requiring motion within three degrees of freedom and. However, participants were slower completing game tasks requiring motion within six degrees of freedom when using the optical tracker; they took a longer time and had more difficulty in completing tasks with motion in the sagittal plane when using the optical tracker. Thus, the low-cost and technically simple optical tracking device appears to be suitable for functional tasks that are not too complex.

The overall goal of the current study was to investigate the usability of the Virtual Wrist Tracker (VWT), an adapted version of Yeh et al.'s (2008) optical tracking device, as a dynamic, clinical measurement tool of wrist movement. This goal was achieved by exploring five objectives:

1. To adapt the original device to meet the ergonomic criteria needed to perform clinical assessment or patients with orthopaedic injury.
2. To determine the test-retest reliability of the VWT system.
3. To compare ROM measured via a goniometer to that measured via the VWT.
4. To determine the discriminant validity of the VWT by comparing differences in range of motion between a group that has sustained a wrist injury and a control group without upper limb injuries.
5. To compare the ROM of the wrist using the VWT to guide performance of tasks with different types of feedback interactivity within a virtual environment.

2. METHODS

2.1 Participants

The research group included 15 adult participants with wrist fractures who were referred to occupational therapy specialists in hand rehabilitation at the Sheba Medical Center, Israel, during a five month period in 2009. Eight participants had wrist fractures of their right hand (53.3%), and seven had fractures of their left hand (46.7%). Nine of the participants had surgery to repair the fracture (60%). The control group included 15 healthy participants who were matched to the research group for age, gender, dominant hand and profession (Table 1).

2.2 Virtual Wrist Tracker (VWT)

Yeh et al.'s (2008) optical tracking device was adapted to improve the hand grip and to provide support for the forearm (Fig. 2). These adaptations were carried out by an occupational therapist and mechanical engineering to comply with ergonomic criteria while maintaining the biomechanical alignment of the device. In the current setup, a single web camera was used, positioned to capture sagittal plane motion (wrist flexion and extension). A close-up view of the tracking device with its dual LEDs is shown in Fig. 3.

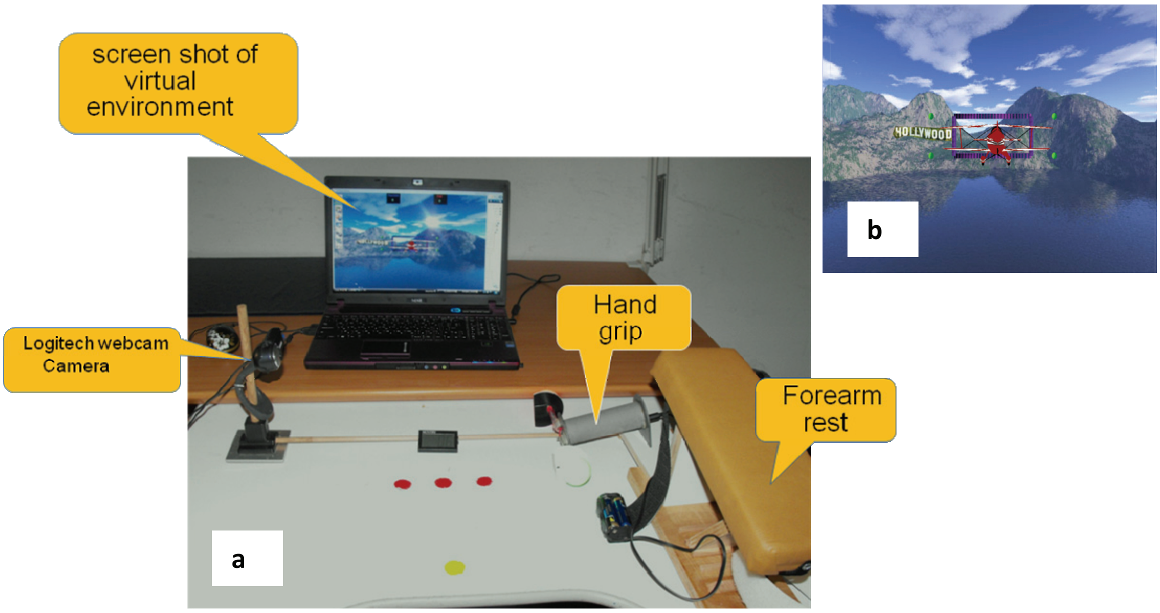

Figure 2. *(a) Experimental setup of the adapted hand-held LED unit with hand grip, forearm rest support, web camera positioned to record motion in sagittal plane and screen shot of virtual environment. (b) enlarged screen shot of the virtual environment showing the airplane and target rectangle.*

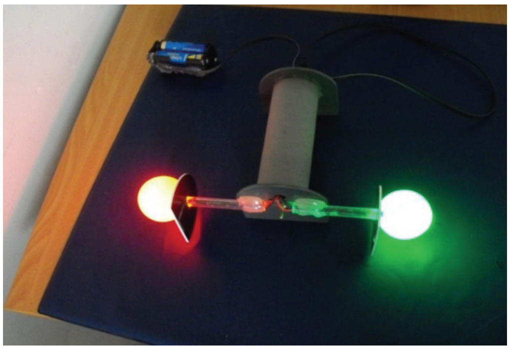

Figure 3. *Hand-held dual LED unit with adapted hand grip.*

2.3 Outcome measures

A demographic questionnaire was used to record participant details including their gender, age, and hand dominance as well as details about their medical condition in the case of the patients. The Functional Status Questionnaire (FSQ) is a 34-item, self administered questionnaire to assess the physical, psychological and social functional status of ambulatory patients (Jette et al., 1986). The Disabilities of the Arm, Shoulder and Hand (DASH) Questionnaire is a 30-item self-report condition-specific questionnaire that measures physical function at the level of disability, evaluating a patient's ability to perform an activity, regardless of how it is done. Lower scores on the DASH reflect less disability and higher scores reflect more disability (McConnell et al., 1999; Beaton et al., 2001). The Short Feedback Questionnaire (SFQ) is a 6-item questionnaire that queries the participant's (1) feeling of enjoyment, (2) sense of being in the environment, (3) success, (4) control, (5) perception of the environment as being realistic and (6) whether the feedback from the computer was understandable (Kizony et al., 2006). Responses to all questions were rated on a 5-point scale, which were combined to give a global response to the experience for a maximum score of 30. An additional question asked whether the participant felt any discomfort during the experience.

Wrist extension and flexion were measured by a standard goniometer and the kinematic output from the VWT was recorded and the maximum flexion and extension ROM of each condition (one with full visual and auditory feedback and one with auditory pacing feedback) and at selected targets (see below) was determined.

2.4 Procedure

Wrist flexion and extension ROM were then assessed with a conventional wrist goniometer. The participants then performed a series of tracking tasks (one each of flexion and extension) while using the VWT VR system under two, counter-balanced conditions. During Condition A (visual and auditory feedback) the participants were able to view the up and down motion of an airplane that they controlled via wrist flexion (down) or extension (up). The magnitude of the ROM was elicited by the position of 15 target rectangles through which the airplane was supposed to pass. The position of successive rectangles was increased to elicit greater ROM as the trial continued. During Condition B (auditory pacing) the participants were requested to perform a similar series of 15 flexion or 15 extension movements but were provided with auditory tempo cues only (the visual display was masked). At the end of each condition, the participants completed the SFQ. The participants' completed the demographic questionnaire, the FSQ, and the DASH at the end of the session. The healthy participants performed two consecutive tests of the visual and auditory feedback condition in order to determine the VWT's test-retest reliability.

2.5 Statistical analysis

SPSS version 17 was used to process the data; the significance level for all of the analyses was set at 0.05. The Intraclass Correlation Coefficient (ICC) was calculated to determine the test-retest reliability of the VWT. Repeated measures mixed design analysis of variance (ANOVA) were calculated to determine differences in wrist flexion and extension ROM between the research and control groups, between the two display conditions and between three target rectangles (i.e. 4th, 9^{th} and 15^{th} target positions).

3. RESULTS

3.1 Participant characteristics

Table 1 shows the participants' demographic, medical and functional characteristics. The mean (SD) age of the research group was 45.0 (15.2) years with 10 males and 5 females. The mean (SD) age of the control group was 45.5 (15.7) years with the same gender distribution. Eight of the patients sustained a right wrist fracture and 7 had a left wrist fracture. As expected, the DASH and FSQ scores for the research group indicate a residual disability (DASH) and decreased functional status (FSQ).

Table 1. *Participant demographic, medical and functional characteristic.*

	Research Group (N=15)	Control Group (N=15)
Male:Female	10:5	10:5
Age – mean (SD)	45.0 (15.2)	45.5 (15.7)
Hand dominance (Right:Left)	12:3	12:3
Wrist fracture (Right:Left)	8:7	N/A
Internal fixation (Yes:No)	9:6	N/A
DASH – mean (SD)	45.8 (17.6)	1.9 (1.9)
FSQ – mean (SD)	100.4 (15.6)	129.7 (11.0)

3.2 Test-retest reliability

The ICC was used to determine the test-retest reliability of wrist flexion and extension ROM as measured by the VWT) during two sequential measurements performed by the control group. The results indicate high reliability for wrist extension (r=.924, p=.001,) and moderate reliability for wrist flexion (r=.488, p=.024).

3.3 Validity of wrist ROM

Table 2 shows the means and standard deviations of the wrist flexion and extension ROM of the research and the control groups when measured with a standard goniometer and when recorded during the performance of two conditions, one with full visual and auditory feedback and one with auditory pacing feedback. It is evident that the mean values for the research group are considerably lower than those of the control group for both flexion and extension movements during all three conditions. High, significant correlations were found between the ROM for wrist extension (r=0.641, p<.05) and flexion (r=0.654, p<.01) as measured by a goniometer and via the VWT in the research group and for wrist extension (r=0.761, p<.01) but not for wrist flexion in the control group.

Table 2. *Means and standard deviations of the maximum ROM in the research and control groups for the two VWT conditions.*

	Maximum Range of Motion (degrees)			
Condition	Mean (SD) Flexion		Mean (SD) Extension	
	Research Group	Control Group	Research Group	Control Group
Goniometer	41.0 (10.2)	75.3 (7.2)	36.3 (10.3)	71.0 (8.1)
Condition A (visual & auditory feedback)	56.6 (14.3)	77.8 (6.8)	39.0 (12.7)	70.5 (9.2)
Condition B (auditory pacing feedback)	55.7 (12.0)	82.3 (11.9)	41.6 (14.1)	65.9 (14.5)

A repeated measures mixed design ANOVA was performed to test for differences in wrist extension and flexion ROM between the research and control groups during the two feedback conditions. There was no significant difference in wrist extension ROM during the performance of the task with visual and auditory feedback versus a task with auditory pacing (F(1,28)=.19, p>.05), nor was there an interaction effect between task type and group (F(1,28)=2.42, p>.05) (see Fig. 4a). Nor was a significant difference found in the range of motion for wrist flexion during the performance of the visual and auditory feedback task versus the auditory pacing task (F(1,28)=.64, p>.05); neither was there an interaction between the feedback condition and the group is not statistically significant as well (F(1,28)=1.45, p>.05) (see Fig. 4b).

The data in Table 3 show the mean maximum range of motion for wrist flexion and wrist extension for both the research and control groups when the participants traversed three of the 15 target rectangles (#4, #9, #15). It is evident that the ROM in either direction increased as the participant progressed from one target rectangle to the next.

Wrist extension ROM during the visual and auditory task at the target rectangles differed significantly for the combined data (both research and control groups) (F(2,56) = 236.54, p<.001). ROM at target rectangle 4 was significantly smaller than ROM at target rectangle 9 (F(1,28) = 260.77, p<.001) and ROM at target rectangle 9 was significantly smaller than ROM at target rectangle 15 (F(1,28) = 130.59, p<.001). In addition, ROM of the control group was significantly higher than ROM of the research group (F(1,28) = 45.56, p<.001) .A statistically significant interaction effect was found between ROM in target position (3 rectangles) and group (F(2,56)=51.49, p<.001) indicating that the difference between rectangle 4 and 9 and 9 and 15 within the control group was significantly different than in the research group (Fig. 5a).

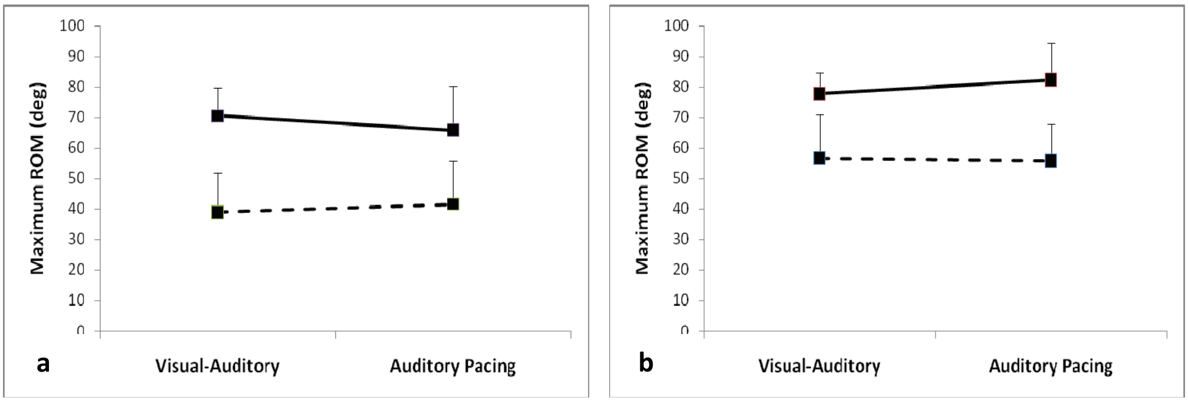

Figure 4. *Mean maximum range of motion with one standard deviation for (a) wrist extension and (b) wrist flexion during the performance of a visual and auditory feedback task versus a auditory pacing task, in the research (dashed line) and the control (solid line) groups.*

Table 3. *Means and standard deviations of the ROM at three different target "rectangles" (4, 9, 15) by the research and control groups*

		Range of Motion (degrees)			
	Target Rectangle	Mean (SD) Flexion		Mean (SD) Extension	
		Research Group	Control Group	Research Group	Control Group
Condition A	4	20.4 (4.4)	21.3 (3.8)	20.7 (3.3)	23.3 (4.6)
	9	43.1 (12.3)	48.3 (4.6)	34.4 (9.3)	47.1 (3.2)
	15	55.5 (14.9)	76.6 (6.3)	38.2 (12.9)	70.5 (9.2)
Condition B	4	26.8 (16.0)	31.6 (24.0)	20.5 (11.0)	23.3 (22.9)
	9	48.7 (13.8)	59.7 (25.7)	36.0 (13.0)	49.5 (19.3)
	15	54.8 (11.8)	81.5 (11.1)	41.1 (14.2)	65.6 (14.4)

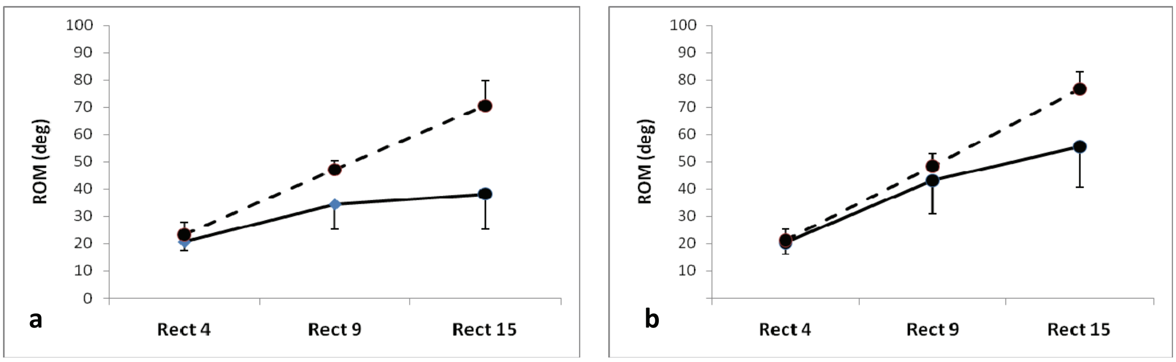

Figure 5. *Maximum range of motion with one standard deviation for (a) wrist extension and (b) wrist flexion at three target rectangles (4^{th}, 9^{th}, 15^{th}) during the performance of the visual and auditory feedback task by the research (solid line) and control (dashed line) groups.*

Results for wrist extension ROM during the auditory pacing task at the target rectangles were similar to those described above for the visual and auditory feedback task with significant differences for the combined data (both research and control groups) (F(2,56) = 75.00, p<.001). ROM at target rectangle 4 was significantly smaller than ROM at target rectangle 9 (F(1,28) = 75.39, p<.001) and ROM at target rectangle 9 was significantly smaller than ROM at target rectangle 15 (F(1,28) = 29.21, p<.001). In addition, ROM of the control group was significantly higher than ROM of the research group ($F(1,28) = 6.96$, $p<.05$) A statistically significant interaction effect was found between ROM in target position (3 rectangles) and group ($F(2,56)= 8.62$, $p<.001$) indicating that the difference between rectangle 4 and 9 and 9 and 15 within the control group was significantly different than in the research group (Fig. 5a).

Wrist flexion ROM during the visual and auditory task at the target rectangles differed significantly for the combined data (both research and control groups) ($F(2,56) = 332.06$, $p<.001$). ROM at target rectangle 4 was significantly smaller than ROM at target rectangle 9 ($F(1,28) = 258.20$, $p<.001$) and ROM at target rectangle 9 was significantly smaller than ROM at target rectangle 15 ($F(1,28) = 171.02$, $p<.001$). In addition, ROM of the control group was significantly higher than ROM of the research group ($F(1,28) = 13.12$, $p<.01$) A statistically significant interaction effect was found between ROM in target position (3 rectangles) and group ($F(2,56)= 18.38$, $p<.001$) indicating that the difference between rectangle 9 and 15 in the control group was significantly different than in the research group (Fig. 5b).

Results for wrist flexion ROM during the auditory pacing task at the target rectangles was similar to that described above for the visual and auditory feedback task with significant differences for the combined data (both research and control groups) ($F(2,56) = 86.12$, $p<.001$). ROM at target rectangle 4 was significantly smaller than ROM at target rectangle 9 ($F(1,28) = 74.63$, $p<.001$) and ROM at target rectangle 9 was significantly smaller than ROM at target rectangle 15 ($F(1,28) = 27.85$, $p<.001$). In addition, ROM of the control group was significantly higher than ROM of the research group for ($F(1,28) = 6.39$, $p<.05$) A statistically significant interaction effect was found between ROM in target position (3 rectangles) and group ($F(2,56)=7.03$, $p<.05$) indicating that the difference between rectangle 9 and 15 in the control group was significantly different than in the research group (Fig. 5b).

3.4 Participant responses to VWT

Participants in both groups reported that they enjoyed the VWT task (mean (SD) SFQ item 1= 3.9 (0.9) for the research group and 3.9 (1.2) for the control group. The control group felt a greater sense of being in the environment (SFQ item 2= 3.5 (1.5)) than did the research group (SFQ item 2= 2.9 (1.4)). They also reported more success during the task (control group SFQ item 3= 4.1 (0.6) versus research group SFQ item 3= 3.1 (0.9)) and a greater sense of control (control group SFQ item 4= 4.4 (0.7) versus research group SFQ item 4= 3.1 (1.1)).

4. CONCLUSIONS

This study was designed to evaluate the usability, reliability and validity of a simple optical tracking device, the Virtual Wrist Tracker, for the clinical assessment of wrist flexion and extension. The VWT demonstrated moderate to good reliability and showed high, significant correlations between the ROM measured by a goniometer and via the VWT. Changes in target rectangle position enable the clinician to evaluate the change in ROM along the task. Both groups enjoyed performing the VWT tasks but the control subjects felt greater presence, success and control. Overall, the VWT appears to be a suitable tool for assessing wrist ROM during dynamic activities.

The results of this study provide support for the use of simple, markerless motion capture device for a variety of clinical applications including the diagnosis and assessment of joint ROM, monitoring of the effectiveness of treatment, determination of the readiness to return to work and other daily activities, and evaluation of permanent incapacity (Fess, 1986).

Future work should examine the ability of such devices to provide treatment for wrist injuries. Considerable evidence has accumulated regarding the use of virtual environments as a means for implementing physical exercises in a game-like setting that is highly motivating for users (Rizzo and Kim, 2005; Rand et al., 2008). However, until recently, environments run on video capture based equipment were either very (e.g., the CAREN VR system *www.motekmedical.com/*) or moderately (e.g., the IREX system *www.gesturetekhealth.com/*) costly. Other options, such as the Sony Playstation II EyeToy, are not readily adaptable to the abilities of people with injuries (Rand et al., 2008) or are only available as customized units. The VWT was constructed with low cost parts and operates with a simple web camera. Yet, it can be easily adapted to provide assessment and training targets. It thus appears to be a tool well suited for routine use in clinical settings.

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