Motor Indicators for the Assessment of Frozen Shoulder Rehabilitation via a Virtual Reality Training System

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Abstract: Adhesive capsulitis (also known as frozen shoulder) is a common clinical shoulder disorder and can be effectively improved through physical rehabilitation. With advancements in technology, virtual reality (VR) has been increasingly employed in rehabilitation treatments. However, most relevant studies have merely employed traditional assessment tools to assess the therapeutic effects rather than the substantial amount of motor trajectory data or task performance collected by motor training systems. In this research, an innovative frozen shoulder rehabilitation system using a Microsoft Kinect sensor and VR was successfully developed and five task-oriented motor indices and task performance were proposed to assess motor performance. A clinical experiment involving twenty patients was conducted. Objective clinical assessment outcomes verified the effectiveness of the developed system for frozen shoulder rehabilitation. The improvements assessed according to motor indices and task performance were consistent with the objective clinical assessment results. Furthermore, correlation analysis showed that several items in the task performance and motor indices were significantly correlated to clinical assessment items. Moreover, numerous items in the task performance and motor indices capable of predicting the clinical assessment results were identified through stepwise regression analysis. The results of this research can facilitate the subsequent development of new assessment methods.

Keywords: frozen shoulder; motor assessment; rehabilitation; virtual reality (VR)

1. Introduction

Frozen shoulder is a general term that refers to damage of the soft tissues, articular capsule, and joint cavity of the shoulder, and is a clinically common shoulder disorder. The goal for frozen shoulder treatments is to maintain and improve shoulder ROM and enhance muscle strength, thereby allowing patients to resume their normal activities as soon as possible [1]. Medicinal treatments include the consumption of medicines and steroid injections in the shoulder joints to relieve pain. However, the effects of medicinal treatments for patients with serious illness are limited. Therefore, alternative physical therapies are necessary to restore function in the shoulder joint [2]. Such physical therapies should emphasize the performance of appropriate articulated movements, stretches (including Codman exercises [3], pulley therapy, forward and sideways finger wall walking, and the towel exercise) [4,5], and joint mobilization exercises.

In recent years, because of the advancements in technology, many researchers have employed virtual reality (VR) technology in rehabilitation therapies [6–9] which show the feasibility and usability of proposed VR system. Combining this technology with task
design enhances the appeal of rehabilitation treatments [10], which increases patients’ motivation [11] and maximizes the therapeutic effects [12,13], indicating the effectiveness of VR-based rehabilitation system. Particularly, along with the progress of technology at motion capture, researchers have begun employing Microsoft Kinect™ (Microsoft Corp®, Redmond, WA, USA) [14] for motor rehabilitation because of its ability to capture joint trajectories throughout the entire body, and that users can perform natural movements because they do not need to wear a device. Lange et al. [15] integrated Microsoft Kinect™ with VR to develop a rehabilitation training system for patients with stroke or spinal cord injuries. Gama [16] collected skeleton data using Kinect sensors to establish a data model of standard movement, which was subsequently used to assess the movement accuracy of patients undergoing rehabilitation. However, Gama did not conduct experiments with clinical cases; therefore, the effectiveness of the model could not be verified.

However, in previous research regarding the integration of motor rehabilitation and VR, the VR system was typically only employed as motor training system. Task performance or the motor trajectories obtained by the motor training system were not employed as the basis for assessing therapeutic effects. Instead, assessments were conducted only before and after rehabilitation treatments by using traditional clinical assessment tools. For example, Henderson et al. [17] adopted VR as a tool for stroke rehabilitation and used the Fugl-Meyer arm scale (FMA) and the manual function test (MFT) as the primary bases for assessment. The results of motor training tasks designed as games by Pastor et al. [18] showed a substantial increase in task performance scores after treatments although no noticeable increase in the FMA results were observed. However, Pastor et al. failed to conduct an in-depth investigation of the relationship between task performance and therapeutic effects.

This study used VR technology combined with Kinect interaction technology to develop an innovative VR-based interactive shoulder rehabilitation (VRISR) system that enables patients diagnosed with frozen shoulder to perform rehabilitation exercises, including flexion, abduction, internal rotation, external rotation, and circumduction. The research objectives of this study were to (1) establish a new VRISR system; (2) develop new task-oriented motor indices through clinical experiments to assess motor performance using motor trajectories and by integrating VR task content with task goals; and (3) investigate the correlation of the proposed motor indices and the system task performance with traditional clinical assessment outcomes, as well as the predictability of the proposed system to establish new reliable assessment methods.

2. System Design and Motor Indices
2.1. System Architecture and Task Design

For the VRISR, seven situated VR tasks, based on three categories of rehabilitation movements: forearm extension, shoulder-elbow exercise, shoulder joint internal/external rotation, were constructed via game-developing software Unity 3D. Microsoft Kinect was employed to detect user movements and collate data of the upper limb bones to monitor the location of users’ hands. Patients were able to instantly control the target objects to achieve the task goals. The VR tasks equipped with multiple sensory feedback designs and hierarchical challenges. Scene of virtual environment was projected onto a wall. Users stood facing the wall with their arms stretched upward resting on the wall, which provided a reaction force; this is known as passive haptics. Task performance and motor trajectories were recorded in a database for subsequent motor analysis. The system architecture is presented in Figure 1.
2.2. Motor Indices

While performing the VR tasks, patients’ motor trajectories were recorded to develop new task-oriented motor indices for assessing motor performance. However, these motor indices were not established by merely analyzing the patients’ motor trajectories. Instead, they were developed by integrating the data of motor trajectories and task content and goals. Only one task from each exercise category was selected to develop the proposed motor indices.

2.2.1. Forearm Extension

The Tracing task was selected from the various forearm extension training exercises for developing and analyzing relevant motor indices, as shown in Figure 2a. Patients were required to use the hand of the affected side to connect target objects on the left of the screen with objects on the right by following the paths presented on screen. The paths from left to right could be horizontal lines or oblique lines from the upper left side to the lower right side and from the lower left side to the upper right side. The purpose of this design was to enable patients diagnosed with frozen shoulder to slowly stretch and extend their injured shoulder joint. The tracing task was divided into 3 motor modes, as shown in Figure 2b.

The following four motor indices were designed for this task: (1) Efficiency (EF), which was measured according to the ratio of the actual motor trajectory length to the target trajectory length. The closer this ratio is to one, the higher the efficiency. (2) Speed (S), which was measured by dividing the motor trajectory length by the amount of time spent performing the task. S is high when patients spend minimal time using the arm of the injured side to perform tasks. (3) Maximum instantaneous velocity (Vmax), which was assessed according to the instantaneous velocity of the patients’ arm movements. A relatively lower ωmax value indicates high stability, which reduces the likelihood of overshooting. (4) Movement deviation (MD), which was calculated based on the entire time-history root-mean-square error of all deviations from the target paths during the training tasks, as shown in Figure 2c. The error was determined as the distance between the patients’ hand projections and the target path. Comparatively low MD indicates high stability and controllability.
2.2.2. Shoulder-Elbow Exercise

For shoulder-elbow exercise, the Barman VR task was selected for developing and analyzing relevant motor indices, as shown in Figure 3a. For this task, the patients controlled the hands of a bartender in a virtual scene to perform tasks such as obtaining glasses from the bar, pouring drinks into the glasses, and then presenting the glasses filled with drinks. Before performing this task, the patients were instructed to stretch their injured shoulder joint for ten seconds by placing their hands on a white wall. The movements involved in the Barman task were divided into two motor modes, as shown in Figure 3b. Mode 1 involved collecting empty glasses from the lower right of the screen, moving them to the center of the screen, and then filling them with drinks. Mode 2 involved moving the filled glasses to the lower left of the screen.

The motor indices used for this task were EF, S, Vmax, and MD, as defined in Section 2.2.1. The MD index is shown in Figure 3c.
2.2.3. Shoulder Joint Internal/External Rotation

The ship driving task was selected as the shoulder joint internal/external rotation exercise for motor index development and analysis, as shown in Figure 4a. This task also involved flexion and abduction training. As shown in Figure 4b, during the ship driving task, the patients were required to use the hand of the injured side to turn the ship helm clockwise or counterclockwise from the starting point, according to the task instructions. In addition, their hand of the injured side was required to remain within the tolerated zone of the helm until they turned the helm one full circle to complete the task.

The following five motor indices were adopted for the ship driving task: (1) EF, which refers to the ratio of the actual motor trajectory length to the circumference of the inner circle in the target area. The closer the ratio is to one, the higher the efficiency. (2) Rotational velocity (RV), which was determined by dividing the rotational angle of the patients’ shoulder joint during the task by the amount of time spent completing the task. Because the degree to complete a circle is identical $360^\circ$, the less time spent, the higher the RV. (3) The $\omega_{\text{max}}$, which was determined according to the instantaneous angular velocity of the patients’ arm movements. A low $\omega_{\text{max}}$ value indicates high stability, which reduces the likelihood of overshooting. (4) MD, which was calculated based on the entire time-history root-mean-square error of all deviations from the target paths during the training tasks, as shown in Figure 4c. The error was determined according to the distance between the patients’ hand projections and the circumference of the inner circle. Comparatively low MD indicates high stability and controllability. (5) Break point (BP): If the patient’s affected arms lack stability and moves out of the tolerated zone, the VR helm will cease to

![Figure 3. VR task: Barman](image)

(a) VR task: Barman  
(b) Motor modes  
(c) Movement
turn, which is considered one BP, as shown in Figure 4d. A low number of BPs indicates high stability.

![VR task: Ship Driving](image)

**Figure 4.** VR task: Ship Driving.

### 3. Methods and Materials

#### 3.1. Participants

For this experiment, twenty patients diagnosed with frozen shoulder were recruited. The participant inclusion criteria were (1) at least twenty years of age, (2) no previous physical rehabilitation experience, (3) normal cognition and able to cooperate in learning how to use the system, (4) a clinical diagnosis of frozen shoulder, and (5) a signed consent form. Potential participants were excluded for having (1) a shoulder or humerus injury that involved a fracture or dislocation and was treated with surgery, (2) prior shoulder injections of hyaluronic acid, (3) a history of cervical radiculopathy or osteoarthritis in the shoulder, (4) a diagnosis of end-stage malignant disease, and (5) current pregnancy. The participants’ demographic information is presented in Table 1.

#### Table 1. Demographic information of the experiment participants.

| Information                              | The Experiment Group |
|------------------------------------------|----------------------|
| Number of participants                   | 20                   |
| Age                                      | 60.65 ± 11.84        |
| Sex ratio (male/female)                  | 5/15                 |
| Duration of condition (month)            | 12.2 ± 6.2           |
3.2. Intervention

The rehabilitation treatments included in the experiment were motor rehabilitation training, hot compresses, and interferential current therapy. A hot compress and interferential current therapy were administered to the injured shoulder of every participant for twenty minutes twice per week, for a period of four weeks. The rehabilitation training exercises were also performed for twenty minutes twice per week, for a period of four weeks. The experimental group used the proposed VRISR system for rehabilitation training, performing seven VR tasks in a fixed sequence at each training session. The control group performed general rehabilitation exercises that involved similar movements but without situated VR design (Codman exercises and the forward and sideways finger wall walking exercise). A licensed therapist conducted Constant-Murley score (CMS) assessments [19,20] and active and passive shoulder joint angle measurements before and after the rehabilitation treatment.

3.3. Outcome Measures and Analysis

The outcome measures used in this study were clinical assessment tools, task performance, and motor indices.

The clinical assessment tools comprised the CMS and active and passive shoulder joint angle measurements. The active and passive joint angles of the injured shoulder were measured using a standard protractor when performing flexion, abduction, internal rotation, and external rotation. Therapists conducted clinical assessment before and after the treatments without prior knowledge regarding whether the participant belonged to the experimental or control group. Task performance was measured according to the participants’ performance of the seven VR tasks during the training process, and included the number of tasks completed and the time spent completing each task. The motor indices used in this study have been explained in Section 3.2.

To examine the therapeutic effects according to the results of the clinical assessment tools, task performance, and motor indices, the non-parametric statistical Wilcoxon rank sum test was performed to analyze the pretest and posttest clinical assessment outcomes. Note that the normal approximation was adopted to carry out the test statistic. A paired t-test was conducted to analyze the statistics of the first and final (8th) task performance and motor index measurements. It should be noted that the two-sided test was adopted to determine the p-values. Meanwhile, p-values less than 0.05 were declared to be significant. Increases in task performance and motor indices between the first and final training sessions and between the pretest and posttest clinical assessment results were used to analyze the correlation between clinical assessment outcomes and the task performance and motor indices. Moreover, a multi-regression model was used to examine the feasibility of using task performance and motor indices to predict the clinical assessment results.

4. Results

4.1. Clinical Assessment Tools

As shown in Table 2, Table 3, the results of both clinical assessment tools, that is, the CMS and active and passive shoulder joint angle measurements, showed significant improvements after rehabilitation.

Table 2. Summary statistics and Wilcoxon rank sum test for comparing CMS between pretest and posttest.

|        | N  | Mean | SD   | Test Statistic | p-Value |
|--------|----|------|------|----------------|---------|
| CMS    | Pretest | 20  | 58.40 | 1.414          | 3.825   |
|        | Posttest | 20  | 76.50 | 9.490          | <0.01 **|

Significance level = 0.05. * p < 0.05, ** p < 0.01.
Table 3. Summary statistics and Wilcoxon rank sum test for comparing movement angle measurements between pretest and posttest.

|                | N  | Mean   | SD    | Test Statistic | p-Value |
|----------------|----|--------|-------|----------------|---------|
| Flexion Pretest| 20 | 146.590| 17.581| 3.921          | <0.01 **|
| Flexion Posttest| 20 | 161.935| 12.722|                |         |
| Abduction Pretest| 20 | 134.500| 30.956| 3.920          | <0.01 **|
| Abduction Posttest| 20 | 149.620| 24.759|                |         |
| External Rotation Pretest| 20 | 66.480 | 20.607| 3.921          | <0.01 **|
| External Rotation Posttest| 20 | 78.270 | 15.242|                |         |
| Internal Rotation Pretest| 20 | 49.500 | 15.739| 3.783          | <0.01 **|
| Internal Rotation Posttest| 20 | 61.095 | 15.739|                |         |

Significance level = 0.05. * p < 0.05, ** p < 0.01.

4.2. Task Performance

Task performance for the seven VR tasks is shown in Table 4. The patients showed significant improvements in task performance after eight rehabilitation training sessions.

Table 4. Summary statistics and paired t-test for comparing movement task performance outcomes between pretest and posttest.

| VR Tasks          | Session | N  | Mean   | SD    | Test Statistic | p-Value |
|-------------------|---------|----|--------|-------|----------------|---------|
| Tracing 1st       | 20      | 6197.500| 1042.360| 6.217 | <0.01 **      |
| Tracing 8th       | 20      | 7479.500| 501.414  |       |               |
| Reaching for Fruit 1st | 20  | 6501.000| 1775.864| 4.945 | <0.01 **      |
| Reaching for Fruit 8th | 20  | 8403.500| 1504.034|       |               |
| Barman 1st        | 20      | 201.000 | 42.770  | 3.764 | <0.01 **      |
| Barman 8th        | 20      | 160.500 | 21.785  |       |               |
| Spiderman 1st     | 20      | 1913.000| 284.644 | 6.462 | <0.01 **      |
| Spiderman 8th     | 20      | 2244.500| 187.040 |       |               |
| Jungle Adventure 1st | 20  | 2039.000| 287.840 | 3.427 | <0.01 **      |
| Jungle Adventure 8th | 20  | 2233.500| 211.368 |       |               |
| Ladybug Game 1st  | 20      | 3828.750| 65.748  | 4.365 | <0.01 **      |
| Ladybug Game 8th  | 20      | 3910.500| 88.880  |       |               |
| Ship Driving 1st  | 20      | 5028.500| 578.822 | 4.787 | <0.01 **      |
| Ship Driving 8th  | 20      | 5594.500| 189.528 |       |               |

Significance level = 0.05. * p < 0.05, ** p < 0.01.

4.3. Indicator

Regarding the Tracing task, the relevant motor trajectories are shown in Figure 5a. The analysis outcomes of each motor index for the three motor modes are presented in Tables 5–7. The results show significant improvements in the majority of the motor index items. The improvement in EF for the three motor modes did not achieve a level of significance. However, a trend of improvement was observed for the motor indices that did not achieve a level of significance.

Regarding the Barman VR task, the relevant motor trajectories are shown in Figure 5b. The analysis outcomes of each motor index for the two motor modes are presented in Tables 8 and 9. According to the results, more than half of the motor index items exhibited a significant improvement, and a trend of improvement was observed for the items that did not achieve a level of significance.

Regarding the ship driving VR task, the relevant motor trajectories are shown in Figure 5c. The analysis outcomes of each motor index for the one motor mode are presented in Table 10. The results show a significant improvement in all motor indices.
Figure 5. Motor trajectories in the VR task.

Table 5. Summary statistics and paired t-test for comparing motor indices in Mode 1 between the first and eighth training for the Tracing task.

| Motor Index | Session | N  | Mean   | SD     | Test Statistic | p-Value |
|-------------|---------|----|--------|--------|----------------|---------|
| S           | 1st     | 54 | 41.151 | 39.818 | −4.890         | <0.01 **|
|             | 8th     | 54 | 69.844 | 37.693 |                |         |
| EF          | 1st     | 54 | 1.411  | 0.412  | 2.626          | <0.05 * |
|             | 8th     | 54 | 1.263  | 0.208  |                |         |
| MD          | 1st     | 54 | 23.667 | 41.147 | 1.812          | 0.076   |
|             | 8th     | 54 | 13.420 | 7.069  |                |         |
| V_max       | 1st     | 54 | 884.554| 380.055| 4.519          | <0.01 **|
|             | 8th     | 54 | 784.876| 281.033|                |         |

Significance level = 0.05. * p < 0.05, ** p < 0.01.

Table 6. Summary statistics and paired t-test for comparing motor indices in Mode 2 between the first and eighth training for the Tracing task.

| Motor Index | Session | N  | Mean   | SD     | Test Statistic | p-Value |
|-------------|---------|----|--------|--------|----------------|---------|
| S           | 1st     | 72 | 48.839 | 43.532 | −3.802         | <0.01 **|
|             | 8th     | 72 | 70.873 | 36.691 |                |         |
| EF          | 1st     | 72 | 1.476  | 0.349  | 6.047          | <0.01 **|
|             | 8th     | 72 | 1.227  | 0.176  |                |         |
| MD          | 1st     | 72 | 22.761 | 18.742 | 0.876          | 0.384   |
|             | 8th     | 72 | 20.242 | 21.811 |                |         |
| V_max       | 1st     | 72 | 1039.005| 380.055| 4.519          | <0.01 **|
|             | 8th     | 72 | 784.876| 281.033|                |         |

Significance level = 0.05. * p < 0.05, ** p < 0.01.
Table 7. Summary statistics and paired t-test for comparing motor indices in Mode 3 between the first and eighth training for the Tracing task.

| Motor Index | Session | N  | Mean  | SD    | Test Statistic | p-Value |
|-------------|---------|----|-------|-------|----------------|---------|
| S           | 1st     | 54 | 43.902| 36.163| −3.757         | <0.01 **|
|             | 8th     | 54 | 68.203| 37.725|               |         |
| EF          | 1st     | 54 | 1.431 | 0.349 | 5.452          | <0.01 **|
|             | 8th     | 54 | 1.711 | 0.176 |               |         |
| MD          | 1st     | 54 | 21.660| 18.742| 0.401          | 0.690   |
|             | 8th     | 54 | 19.679| 21.811|               |         |
| V_{max}     | 1st     | 54 | 1005.137| 461.475| 3.191          | <0.01 **|
|             | 8th     | 54 | 762.579| 346.501|               |         |

Significance level = 0.05. * p < 0.05, ** p < 0.01.

Table 8. Summary statistics and paired t-test for comparing motor indices in Mode 1 between the first and eighth training for the Barman VR task.

| Motor Index | Session | N  | Mean   | SD    | Test Statistic | p-Value |
|-------------|---------|----|--------|-------|----------------|---------|
| S           | 1st     | 80 | 393.827| 197.634| −5.915         | <0.01 **|
|             | 8th     | 80 | 550.455| 202.976|               |         |
| EF          | 1st     | 80 | 2.371  | 0.948 | 2.043          | <0.05 * |
|             | 8th     | 80 | 2.152  | 1.122 |               |         |
| MD          | 1st     | 80 | 84.673 | 20.669| 2.406          | <0.01 **|
|             | 8th     | 80 | 87.142 | 26.835|               |         |
| V_{max}     | 1st     | 80 | 3619.709| 3749.477| −1.340        | 0.184   |
|             | 8th     | 80 | 4294.762| 3159.136|               |         |

Significance level = 0.05. * p < 0.05, ** p < 0.01.

Table 9. Summary statistics and paired t-test for comparing motor indices in Mode 2 between the first and eighth training for the Barman VR task.

| Motor Index | Session | N  | Mean    | SD    | Test Statistic | p-Value |
|-------------|---------|----|---------|-------|----------------|---------|
| S           | 1st     | 80 | 669.757 | 264.633| −7.205         | <0.01 **|
|             | 8th     | 80 | 928.429 | 283.548|               |         |
| EF          | 1st     | 80 | 1.447   | 0.823 | 0.512          | 0.610   |
|             | 8th     | 80 | 1.389   | 0.533 |               |         |
| MD          | 1st     | 80 | 64.917  | 25.043| 0.879          | 0.382   |
|             | 8th     | 80 | 61.705  | 25.104|               |         |
| V_{max}     | 1st     | 80 | 1789.911| 803.339| −3.968        | <0.01 **|
|             | 8th     | 80 | 2459.512| 1360.866|               |         |

Significance level = 0.05. * p < 0.05, ** p < 0.01.

Table 10. Summary statistics and paired t-test for comparing motor indices between the first and eighth training for the Ship Driving VR task.

| Motor Index | Session | N  | Mean  | SD    | Test Statistic | p-Value |
|-------------|---------|----|-------|-------|----------------|---------|
| EF          | 1st     | 24 | 3.785 | 2.329 | 3.354          | <0.01 **|
|             | 8th     | 24 | 2.487 | 1.070 |               |         |
| RV          | 1st     | 24 | 12.005| 2.557 | −4.071         | <0.01 **|
|             | 8th     | 24 | 15.046| 2.109 |               |         |
| MD          | 1st     | 24 | 36.649| 8.482 | 3.971          | <0.01 **|
|             | 8th     | 24 | 26.760| 6.852 |               |         |
| \omega_{max}| 1st    | 24 | 229.408| 187.948| 2.324          | <0.05 * |
|             | 8th     | 24 | 147.591| 143.552|               |         |
| BP          | 1st     | 24 | 13.08 | 11.942| 3.843          | <0.01 **|
|             | 8th     | 24 | 5.08  | 5.453 |               |         |

Significance level = 0.05. * p < 0.05, ** p < 0.01.
4.4. Analysis of the Correlation Between the Clinical Assessment Outcomes and Task Performance and Motor Indices

The differences between the pretest and posttest results of these three factors were adopted as the possible gains achieved in the rehabilitation training tasks to conduct correlation analysis based on Pearson product-moment correlation coefficients. The results are presented in Table 11.

Table 11. The correlations between the clinical assessments and the task performance and motor indices.

| Task Performance and Motor Indices | Clinical Assessment | CMS       | Flexion   | Abduction | External Rotation | Internal Rotation |
|-----------------------------------|---------------------|-----------|-----------|-----------|-------------------|------------------|
| Task Performance                  | Reaching for Fruit  | 0.685 **  |           |           |                   |                  |
|                                   | Jungle Adventure    | 0.483 *   | 0.625 **  |           |                   |                  |
| Motor Indices: Tracing            | EF (Mode 1)         | −0.711 *  |           |           |                   |                  |
|                                   | V_max (Mode 1)      | −0.740 *  |           |           |                   |                  |
|                                   | EF (Mode 2)         |           |           |           | 0.777 *           |                  |
| Motor Indices: Barman             | S (Mode 1)          |           |           |           | −0.732 *          |                  |
|                                   | EF (Mode 2)         | 0.823 *   |           |           |                   |                  |
| Motor Indices: Ship Driving       | EF                  | −0.819 *  | −0.826 *  |           |                   |                  |
|                                   | MD                  |           | −0.775 *  |           |                   |                  |

Significance level = 0.05 * p < 0.05, ** p < 0.01. Correlation level: 0 ≤ |r| < 0.3: low 0.3 ≤ |r| < 0.7: medium 0.7 ≤ |r| < 1: high.

4.5. Predictive Analysis of the Task Performance and Motor Indices in Relation to the Clinical Assessment Outcomes

By conducting stepwise regression analysis, the explanatory power of task performance and motor indices for the clinical assessment outcomes was examined. In the stepwise regression model, the task performance and motor indices were used as predictors, and the clinical assessment outcomes were used as the dependable variable. As listed in Table 12, the items exhibiting predictive power were identified showing that CMS, flexion, and abduction reached a predictable level.

Table 12. The power of task performance and motor indices for predicting the clinical assessment results according to stepwise regression analysis.

| Predictor        | Dependent Variable | R²   | Adj.R²  | Estimated β | β coeff. | Test Statistic | p-Value |
|------------------|--------------------|------|---------|-------------|----------|----------------|---------|
| Task Performance | Reaching for Fruit | CMS  | 0.469   | 0.440       | 0.004    | 0.685          | 3.991   | 0.001  |
|                  | Jungle Adventure   | Flexion | 0.234 | 0.191       | 0.014    | 0.483          | 2.342   | 0.031  |
| Motor Indices    | Ship Driving-EF    | Flexion | 0.671 | 0.671       | −3.129   | 0.819          | −3.502  | 0.013  |
|                  | Ship Driving-EF    | Abduction | 0.885 | 0.838       | −3.945   | −0.597         | −3.504  | 0.017  |
|                  | Ship Driving-MD    | Abduction | 0.885 | 0.838       | −0.430   | −0.505         | −2.967  | 0.031  |

5. Discussion

In this section, the mirror therapy system for upper limb based on SEMG pattern recognition is implemented to identify the gestures of patients’ intact hand. And the feedback is sent to the phone which is placed on the top of the disabled hand to display the gesture identified, thus achieving the performance of mirror therapy for the upper limb.

In this study, the pretest and posttest scores obtained using objective clinical assessment tools, which possessed reliability and validity, were employed to assess the
therapeutic effects. The results are presented in Table 2. A significant improvement was observed for all items, which indicates that the proposed rehabilitation system can enhance the therapeutic effects. Moreover, this study compared the outcomes of the first and last treatment sessions based on the task performance and motor indices derived from the substantial dataset extracted during the motor training processes. The comparison results showed a significant improvement in most items and a trend of improvement in other items, as shown in Tables 3–10. This implies that the task performance and motor indices derived from the data obtained by the proposed rehabilitation system tend to generate consistent results to those derived using objective clinical assessment tools.

To further explore the feasibility of using task performance and motor indices to assess therapeutic effects, all items of these two factors were considered a spectrum. Correlation analysis between the spectrum and the items of the objective clinical assessment tools, which possessed reliability and validity, was conducted. According to the analysis results, every item of the clinical assessment tools exhibited a correlation with one or more items of the task performance and motor indices, as shown in Table 11. This suggests that the spectrum comprising task performance and motor indices can be used to assess therapeutic effects. However, additional experiment data should be obtained to clarify and quantify the relationship that the task performance and motor indices have with the clinical assessment outcomes.

In addition to that all the clinical assessment items were correlated with one or more items of the task performance and motor indices, the highest number of correlation items was four, which was found in CMS results, indicating a valuable outcome. From a clinical perspective, the CMS alone comprises most of the shoulder joint assessment items. Moreover, compared with the other clinical assessment items, CMS is a relatively crucial indicator for shoulder joint assessments. This indicates that the four items that were correlated to the CMS can be used to develop new assessment tools.

Moreover, regarding the jungle adventure VR task, which was designed to incorporate flexion and abduction movements (as explained in Section 2.2.2), the correlation analysis results showed that the task performance of jungle adventure was significantly correlated with the flexion item in the clinical assessment tools, validating the effectiveness of the task design. Similarly, regarding the ship driving task, which was designed to incorporate flexion, abduction, internal rotation, and external rotation movements (as described in Section 2.2.3), the correlation analysis results showed that the motor indices of ship driving was significantly correlated with the flexion and abduction items in the clinical assessments was significant, validating the task design. In other words, the system designed in this study achieved the expected effects.

Correlation analysis of the five motor indices and clinical assessment items showed that EF had a significant correlation with most of the clinical assessment items (excluding external rotation) when the motor modes were not considered. This indicates that the motor index, EF, can be widely applied to various assessment items as a universal index. However, this perception requires additional experimental data and analysis for validation. Meanwhile, despite that some motor indices showed low correlation with clinical assessment items, there is still great potential to re-examine them if a large scale of clinical trials will be performed in the future.

The seven VR tasks adopted for this study were designed according to various motor rehabilitation goals. Of all the tasks, only ship driving covered all of the rehabilitation goals, including flexion, abduction, internal rotation, and external rotation. Based on the stepwise regression analysis results (Table 12), only the motor indices of the ship driving task successfully predicted the clinical assessment items. This not only corresponds to the proposed design, but also indicates that the ship driving task is an effective and multi-purpose motor training activity that integrates related motor indices.

The research limitation of this study was the limited number of participants. A greater sample size can enhance the inferences based on the research results. Furthermore, the
potential occlusion problem by Microsoft Kinect™ device may also limited the diversity of the VR task designs.

6. Conclusions

This study successfully integrated Microsoft Kinect with VR, and developed an innovative frozen shoulder rehabilitation system that comprised seven VR tasks for shoulder flexion, abduction, internal rotation, external rotation, and circumduction. A clinical experiment was successfully conducted on twenty patients. By using the motor trajectory data collected by the system and combining the VR task content with the task goals, five new task-oriented motor indices and task performances were established for assessing movement performance. Through statistical analysis, the effectiveness of this system for frozen shoulder rehabilitation was validated based on the objective clinical assessment results. The therapeutic effects assessed according to the motor indices and task performance was verified to be consistent with the objective clinical assessment results. Furthermore, the task performance and motor index items significantly correlated to the clinical assessment items were identified through correlation analysis. The task performance and motor index items capable of predicting the clinical assessment results were identified through stepwise regression analysis.

Author Contributions: Methodology, L.L. and S.-C.Y.; software, J.C. and C.-H.Y.; validation, S.-C.Y.; formal analysis, L.L. and J.C.; investigation, L.L.; resources, S.-H.L.; data curation, S.-H.L. and S.-C.Y.; writing—original draft preparation, S.-C.Y. and S.-H.L.; statistics analysis, C.-R.C.; writing—review and editing, S.-C.Y. and L.L.; visualization, L.L.; supervision, S.-C.Y.; project administration, S.-C.Y.; funding acquisition, L.L. All authors have read and agreed to the published version of the manuscript.

Funding: There are no commercial interests of the authors relevant to the subject of the manuscript, and this work has not been submitted elsewhere. This work has been partially sponsored by the China Postdoctoral Science Foundation No. 2020M670993, Pilot project on the basic theory and key technologies of ternary spatial swarm intelligence (19511132000).

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy.

Conflicts of Interest: There are no commercial interests of the authors relevant to the subject of the manuscript, no such conflicts of interest exist, and this work has not been submitted elsewhere.

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