Directional vs Non-directional Modes of Vibrotactile Feedback for Arm Posture Replication

Albert Causo, Le Dung Tran, Song Huat Yeo and I-Ming Chen

Abstract—This paper presents an integrated system for upper limb rehabilitation which uses small inertia-based sensors and vibrotactile feedback devices. Vibrotactile feedback is incorporated together with two Inertial Measurement Units (IMUs) attached at the upper arm and the forearm to measure arm motions. The whole arm posture is modeled using three parameters - wrist position, elbow position, and forearm’s orientation. Two different strategies of utilizing vibrotactile feedback for arm posture replication are discussed in this paper. The vibrotactile feedback is used firstly as a directional indicator and secondly as a non-directional indicator that informs the user of matching errors between the current posture and the target posture. The experiments involve seven student volunteers replicating five different arm postures. Results show that the non-directional vibrotactile feedback enables faster and more accurate arm posture correction.

I. INTRODUCTION

According to the World Health Organization Report (2002), 15 million people worldwide suffer from stroke each year and approximately two thirds of these individuals survive and require rehabilitation [1]. Patients’ ability to carry out skilled upper limb movements like daily living activities is afflicted with motor control problems [2]. Therefore, most rehabilitations involve having the patients repeat arm movements or training to achieve correct arm postures.

Due to the increasing number of patients in rehabilitation centers, it is necessary to develop a home-based low-cost device for arm posture replication and rehabilitation. This device can guide the user in the training process with minimal therapist involvement. A review of recent advances in upper limb stroke rehabilitation using various technologies can be found in [3]. Advanced systems for upper-limb rehabilitation could include small inertia-based sensors and feedback devices like vibrotactile actuators.

Current technology has introduced an Inertial Measurement Unit (IMU) that is able to correctly measure body postures and motions with the combination of accelerometers, gyroscopes and magnetometers. It can be used to determine gait kinematics [4], measure trunk and wobble board displacements [5], and full body motion [6]. Moreover, the IMU has been employed effectively in rehabilitation for detecting and assessing the severity of Parkinson’s disease [7], quantifying hemiparesis by measuring hand paths in pointing tasks [8], and treating idiopathic scoliosis [9].

Vibrotactile feedback plays an important role in rehabilitation. The research in [10] presents a comprehensive review of the technological enhancements of vibrotactile feedback in rehabilitation, sports and information display domains. Vibrotactile feedback provides significant contributions as a stimulator for rehabilitation of hands in stroke and Parkinson patients [11], as wireless sensory feedback system for real-time gait modification [12], balance training [14], motor learning [15], as feedback for gesture correction for upper body [16] and motion replication for arm [17].

For replicating upper limb posture, the use of vibrotactile in providing directional versus non-directional feedback is a fundamental issue to be resolved. Few research that explores directional feedback using vibrotactile actuators exists including the instruction of arm motion for calligraphy in 2D-plane [18], the design of arm posture mapping and replication system in 3D [19]. Thus, the main contribution of this paper is the comparison of vibrotactile feedback usage in providing directional and non-directional indicators arm posture replication.

The rest of the paper is organized as follows. Section II introduces the model for determining complete arm posture, while Section III discusses the system overview. Section IV presents strategies for directional and non-directional vibrotactile feedback. The experiment is presented in Section V, and the results are discussed in Section VI. The paper is concluded in Section VII.

II. MODELING ARM POSTURES

A. Arm model

The arm is modeled as a compound flexible pole with two segments as shown in the Fig. 1, each has a distinct curvature and a range of motion. They are capable of bending and rotating in three dimensions with no significant deformation along their lengths. The left photo in Fig. 1 shows the human arm with two IMUs attached at the upper arm and the forearm. We use three parameters to describe the arm posture: wrist position $(x_f,y_f,z_f)$, elbow position $(x_u,y_u,z_u)$, and forearm rotation $(\phi_f)$.

B. Evaluating the arm posture parameters

The IMU integrates 3 accelerometers, 3 angular rate gyroscopes and 3 magnetometers to provide the angle measured around the $x$-axis (parallel to the ground) or roll ($\phi$), the angle around the $y$-axis (parallel to the ground) or pitch
(ρ) and the angle around the z-axis (parallel to gravity) or yaw (θ). The IMU’s orientation (ϕ_{imu}(t), ρ_{imu}(t), θ_{imu}(t)) is measured with respect to the global magnetic north while its angular velocities (ω_x, ω_y, ω_z) are derived from the three axes of the gyroscope. The angular displacements are calculated by integrating the angular velocities. The IMU accelerometer measurement is used to correct the gyroscope integration error.

To compensate for initial user orientation prior to every experiment, the IMUs are calibrated to the arm coordinate system. The arm’s reference axis is located at the shoulder where the x-axis is parallel to the body plane, the y-axis is perpendicular to the body along the arm and the z-axis is against the gravity vector. To calibrate the IMUs, the user has to stretch his arm forward so that it is perpendicular to the plane of the body with the elbow angle at 180° as shown in Fig. 2a. The orientations of the IMUs are then recorded, and the rotation matrices of the displacement offsets are calculated.

Based on the kinematics using the orientation angles (ϕ_{imu}, ρ_{imu}, θ_{imu}) of the two IMUs attached to the arm, the positions of the wrist (x_f, y_f, z_f) and the elbow (x_u, y_u, z_u) with respect to the shoulder are determined (as presented in [19]), assuming that its position remains fixed during arm movement. The forearm’s orientation is obtained directly from IMU measurement attached to the forearm (ϕ_f(t), ρ_f(t), θ_f(t)).

III. SYSTEM OVERVIEW

A. Protocol for correcting the arm posture

In order to correctly replicate the arm posture, the three parameters will be corrected in the following order:
1) 3D position of the wrist (x_f, y_f, z_f)
2) 3D position of the elbow (x_u, y_u, z_u)
3) Forearm roll (ϕ_f)

The user’s current posture is considered matched to a reference posture if all the parameters are within range of specified thresholds.

In [17] and [19], arm posture was corrected one parameter at a time starting from the shoulder to the forearm. However, that process is more mechanical compared to our proposed method of correcting from the wrist first followed by the elbow, which mimics more closely the human behavior of gross motion correction through the wrist first followed by fine motion adjustment.

IV. FEEDBACK STRATEGIES FOR ARM POSTURE CORRECTION

Two feedback strategies are proposed in this paper. The first is to use vibrotactile feedback to provide directional information. In the second strategy, vibrotactile feedback provides matching error (non-directional information) to the user in replicating an arm posture. The user has to interpret the feedback given by the tactors and determine where to move his arm with respect to the error detected by the system. Two different vibration patterns are used for the different strategies as illustrated in Fig. 3. There are 3 different phases for each type of feedback as described in Table I.

<table>
<thead>
<tr>
<th>Phase</th>
<th>(a) Directional Vibrotactile Feedback</th>
<th>(b) Non-directional Vibrotactile Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No vibration</td>
<td>No vibration</td>
</tr>
<tr>
<td>2</td>
<td>Vibration at a constant frequency (100Hz) where magnitude is half of maximum magnitude</td>
<td>Vibration at a constant frequency (100Hz) where magnitude is inversely proportional to error</td>
</tr>
<tr>
<td>3</td>
<td>Vibration at a constant frequency (200Hz) at maximum magnitude</td>
<td>Vibration at a constant frequency (200Hz) at maximum magnitude</td>
</tr>
</tbody>
</table>
The protocol for arm posture replication starts with correcting the wrist position:

- **Directional vibrotactile feedback**: Six tactors are located at different locations of the forearm as shown in Fig. 4. Assuming a sphere with radius $R_{D,OUTER_E}$ that is concentric with the target wrist position. If the wrist is outside of the sphere, there will be no vibration (Phase 1a). Once the wrist is inside of the sphere, one of the $z$ tactors ($z_1$ or $z_2$) and one of the $y$ tactors ($y_1$ or $y_2$) will vibrate (Phase 2a) to guide the user in moving his wrist along $z$-axis and $y$-axis. Four tactors ($z_1, z_2, y_1, y_2$) vibrate continuously at Phase 3a once the matching errors along the $z$ and $y$ axes are smaller than $T_{D,INNER_E}$. Then either $x_1$ or $x_2$ tactor continues vibrating at Phase 2a to guide the wrist to move along the $x$-axis until the $x$-axis matching error is smaller than $T_{D,INNER_E}$ wherein the two tactors $x_1$ and $x_2$ will vibrate continuously at Phase 3a. Finally, all six tactors vibrate at Phase 3a to tell the user that correction of wrist position is finished.

- **Non-directional vibrotactile feedback**: The thresholds are defined by two spheres with radii of $R_{ND,OUTER_E}$ and $R_{ND,INNER_E}$. Both spheres are concentric with the target wrist position. During Phase 1b, vibrotactile feedback is absent since the wrist position is outside of the sphere with radius $R_{ND,OUTER_E}$. Once the wrist is within the range of $[R_{ND,INNER_E}, R_{ND,OUTER_E}]$, Phase 2b begins. When the wrist position is within the permissible deviation (i.e., the wrist is within the sphere with radius $R_{ND,INNER_E}$), the vibration magnitude is set to the maximum, and the vibrotactile motor vibrates continuously (Phase 3b).

The next parameter to be corrected is the elbow position. For the elbow position correction, the reference position is computed to determine whether it lies above or below the arm plane defined by the wrist, the elbow, and the shoulder. For both directional and non-directional vibrotactile feedback, the threshold for the elbow correction is defined as a sphere with radius $R_{INNER_E}$ and concentric with the target elbow position.

- **Directional vibrotactile feedback**: either tactor $z_1$ or $z_2$ together with either tactor $y_1$ or $y_2$ vibrate at Phase 2a to indicate in which direction the elbow should move. Phase 3a occurs when the elbow is within the threshold sphere.

- **Non-directional vibrotactile feedback**: Vibrotactile feedback is absent as long as the elbow is moving in the wrong direction, i.e., opposite the location of the reference position w.r.t. the arm plane. Phase 2b begins when the elbow moves to the correct direction. Finally, correction enters Phase 3b when the location of the elbow falls within the threshold sphere (i.e., a sphere with radius $R_{INNER_E}$).

For the correction of the forearm roll, the permissible range of deviation is defined to be $\Delta \phi_f$.

- **Directional vibrotactile feedback**: one of tactors on the side (either tactor $y_1$ or $y_2$) starts vibrating in Phase 2a to indicate the rotation direction. Once the forearm roll is within the $\Delta \phi_f$ threshold, the tactors vibrate as in Phase 3a.

- **Non-directional vibrotactile feedback**: Phase 1b occurs when the forearm rotates in the opposite direction (i.e., clockwise or counter-clockwise) as the reference angle. As soon as the forearm moves in the right direction, Phase 2b begins. Once the forearm roll angle is within the $\Delta \phi_f$ threshold, Phase 3b starts.
V. EXPERIMENTS

A. Subjects

Seven student volunteers from the university, with ages 20-27 years, participate in the experiments. All were healthy and without any medical condition that could have affected their tactile sensitivity.

B. Postures

Five postures are selected as references for the experiments and illustrated in Fig. 7. Some of the postures are at the anterior (postures 1, 2, 3) and posterior (postures 4, 5) of the body. Postures 1 to 3 are quite easy to execute, while postures 4 and 5 could be challenging due to their unnaturalness, requiring extra effort to execute despite their apparent simplicity.

C. Hardware setup

Two IMUs are placed on the subject’s arm, one is near the elbow and the other is near the wrist. The number as well as the placing locations of tactors for the vibrotactile feedback differs for each strategy.

For direction experiment, we need a total of six tactors: four tactors are placed around the subject’s forearm symmetrically while the other two tactors are placed along the forearm (Fig. 5a). For non-directional feedback, two tactors are placed around the subject’s wrist, one on each side (Fig. 5b). The distance between two tactors should be larger than the two-point discrimination threshold for both male and female as determined in [21]. This threshold is at least 40 mm for either male or female regardless of the location on the arm. The tactors, secured in a holder, are attached to the underside of an elastic band to fit the arms of different subjects. The digital controller is inside the black box. The IMUs connect to the computer via a 2.4GHz wireless system and the vibrotactile feedback unit via Bluetooth.

D. General Procedure

Fig. 6 illustrates the set-up for directional and non-directional experiments. The student is strapped to a chair to minimize shoulder movement; two IMUs are attached to the forearm and the upper arm. A set of vibrotactile feedback unit with 6 tactors for directional experiment and 2 tactors for non-directional experiment is attached to the forearm. The experiments require a master, who establishes the reference posture, and students, who must copy the reference posture. The students must replicate all five postures in Fig. 7, selected in random order for the two set of experiments: directional and non-directional vibrotactile feedback. Each student completes the set of directional experiment, followed by the set of non-directional experiment one week after to make sure the student does not remember the five replicated postures.

For each experiment, whether directional or non-directional experiment, the following procedures are followed:

1) The master wears two IMUs and assumes the reference posture.

2) The student wears two IMUs and one vibrotactile unit (Fig. 5).

3) The student stretches out his arm in front to calibrate the IMU coordinate system.

4) The student assumes the starting position: arms on the side.

5) The student starts correcting arm posture with respect to the randomly selected reference.

For directional experiment:

a) The student starts correcting his wrist position (w.r.t. x, y and z axes of the arm coordinate system). If the tactor is not vibrating, it means that the wrist is far from the target (Phase 1a).

b) Once the wrist is within the set threshold, one of the tactors will vibrate at 100Hz and half of maximum vibrating magnitude (Phase 2a) to guide the user which direction to move (y and z directions).

c) The student must continue moving his wrist in the current direction of motion until the vibration pattern changes to a higher frequency (200 Hz) and the highest magnitude (Phase 3a). The correction in the y and z axes is done. The student should wait until Phase 3a stops (after 2 s) before carrying out the mapping for the next parameter.

d) Steps 5b to 5c are repeated for the x axis.

e) After the wrist position is corrected, the student starts adjusting the elbow position and forearm roll by following the direction provided by the tactors from Phase 2a until Phase 3a ends.

For non-directional experiment:

a) The student starts correcting his wrist position. If the tactor is not vibrating, it means that he is far from the target or moving (for elbow) or rotating (for forearm) in the wrong direction (Phase 1b).

b) Once the wrist comes within the set threshold (or correct direction, in the case of the elbow and forearm), the tactors would vibrate at 100Hz. The magnitude of vibration is inversely proportional to the distance from the reference position (Phase...
2b).

c) The student must continue moving his arm in the current direction of motion until the vibration pattern changes to a higher frequency (200 Hz) and the highest magnitude (Phase 3b). The student should wait until Phase 3b stops (after 2 s) before carrying out the mapping for the next parameter.

d) Steps 5a to 5c are repeated for the next posture parameter until all parameters are exhausted.

For the comparison of the subject’s performance, the master’s posture is recorded first and just loaded up at the beginning of each experiment. The set of threshold values for both directional and non-directional experiment are listed in Table II. The mapping time to replicate one arm posture is recorded once Phase 3 (a or b) of the last parameter matching (e.g., the forearm roll) stops. Concurrently, the system will determine the final matching errors for the set of mapping parameters.

**TABLE II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrist (Direction)</td>
<td>( R_{D,\text{OUTERW}} ) 300 mm</td>
</tr>
<tr>
<td>Wrist (Direction)</td>
<td>( T_{D,\text{INNERW}} ) 15 mm</td>
</tr>
<tr>
<td>Wrist (Non-direction)</td>
<td>( R_{ND,\text{OUTERW}} ) 200 mm</td>
</tr>
<tr>
<td>Wrist (Non-direction)</td>
<td>( R_{ND,\text{INNERW}} ) 25 mm</td>
</tr>
<tr>
<td>Elbow</td>
<td>( R_{\text{INNERE}} ) 25 mm</td>
</tr>
<tr>
<td>Forearm ( \varphi_f )</td>
<td>10°</td>
</tr>
</tbody>
</table>

**VI. RESULTS AND DISCUSSION**

We compared the performance of using the two vibrotactile feedback strategies in correcting the arm posture by evaluating the total mapping time (how long it takes to replicate a posture) and the accuracy (w.r.t each parameter of the reference posture).

Fig. 8 shows the graph of the average mapping time of seven subjects for five postures and two different vibrotactile feedback. The mapping time is slightly different between the two feedback modes as well as among five postures. Overall, the non-directional vibrotactile feedback allowed for faster arm posture replication (36.82 s) as listed in Table III. For the more complex posture (#1) and more unnatural posture (#5), the mapping time for the non-directional vibrotactile feedback is significantly less than the mapping time for the directional vibrotactile feedback.

**TABLE III**

<table>
<thead>
<tr>
<th>Feedback Strategy</th>
<th>Mapping Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direction</td>
<td>52.68 ± 17.98</td>
</tr>
<tr>
<td>Non-direction</td>
<td>36.82 ± 19.37</td>
</tr>
</tbody>
</table>

The accuracy of the two feedback strategies is evaluated through three parameters: wrist position, elbow position and forearm roll. The average error for the five postures among the seven students is listed in Table IV. The sources of measurement errors may arise from the shoulder’s movement that we try to minimize by strapping the subject to a chair during experiment. The other reason may be the sensitivity of IMU due to either the tremor of the arm that is unlikely to be avoided or the tactor’s vibration (when factors are placed near the IMU). As the strategy for correcting the elbow and the forearm roll is the same for both feedback strategies, the error is also similar. On the other hand, the non-directional vibrotactile feedback provides smaller wrist position’s error. This is due to the mapping process of wrist position in directional strategy. The process is broken down into sub-steps where correction happens for every axis sequentially as compared to the simultaneous 3D position correction for the non-directional strategy. The average errors of seven subject for each posture are shown in details in Fig. 9 for the wrist position, Fig. 10 for the elbow position, and Fig. 11 for the forearm roll.

Based on the results, the non-directional vibrotactile feedback may be viewed as the better feedback mode in arm posture replication. It provides both shorter mapping time and higher accuracy in arm posture replication.
Fig. 9. Average wrist position error of seven subjects for five postures.

Fig. 10. Average elbow position error of seven subjects for five postures.

Fig. 11. Average forearm roll error of seven subjects for five postures.

VII. CONCLUSION

In correcting arm posture, the arm was modeled with three parameters: the wrist position, the elbow position, and the forearm roll. Details of measuring the arm posture using IMUs and correcting posture using vibrotactile feedback have been discussed. This paper presents the comparison between directional and non-directional vibrotactile feedback in arm posture replication. The results show that the non-directional vibrotactile feedback provides shorter mapping time as well as higher accuracy for almost all postures tested.

For future work, the comparison between directional and non-directional vibrotactile feedback will be evaluated by incorporating vision feedback instead of only vibrotactile feedback. Additionally, the work is currently underway in designing rehab modules that utilize vibrotactile feedback for use in actual stroke rehabilitation. By understanding the dynamics of vibrotactile feedback in posture replication, we hope to contribute to the design improvements of robotic systems in rehabilitation. This in turn could help realize home-based and patient-initiated health care, especially for stroke rehabilitation.

REFERENCES