A tactile shirt for teaching human motion tasks

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Abstract— **This paper presents a simple prototype of a lightweight sensing and tactile communication system that allows bidirectional communication between two humans, or between a human and a computer. This system tracks the user's actions with simple sensors, and uses tiny vibration motors as feedback devices. Vibration motors provide feedback that is both intuitive and minimally intrusive. The design is simple, flexible, and extensible to large-scale, full-body motion tasks.**

I. INTRODUCTION

This paper presents first steps towards the design of a lightweight sensing and tactile communication system that allows bidirectional communication between two humans, or between a human and a computer.

We are motivated by a particular application: teaching a human physical motions for athletics, rehabilitation, or recreation. Teaching someone to swim, dance, do yoga, or play a musical instrument is hard: precise, simultaneous placement or quick movement of parts of the body is hard to observe, explain, and execute. While platforms such as Khan Academy, Coursera, codeacademy, and edX have democratized the spread of information, the focus has largely been on traditional academic disciplines where the task is non-physical. In the long term, we would like to bring the benefits of online teaching into the physical world.

There are different types of human physical tasks, each with its own challenges. **Posing** tasks include yoga and posture improvement for standing or sitting. The challenge is to achieve a particular configuration, possibly requiring some balancing of internal and external forces, and to maintain that configuration for a duration. **Motion** tasks such as swimming or gymnastics require a sequence of poses to be achieved, continuously and at speed. However, in some cases, training of the human may be done at a very slow speed, as long as body stability can be maintained at slower speeds. **Fine manipulation** tasks such as playing an un-fretted string instrument or painting require small-scale control of motion with high precision.

In preliminary work, we designed a system that allowed us to "program" a blindfolded human to fold a shirt and to navigate a room. Motion capture detects configurations; vibrating motors sewn into a suit direct motion of the arms, hands, and body.

We start with a brief overview of related systems in section II. In Section III we provide a high level design overview. Section IV describes the motion feedback system in detail, and in Section V we discuss lessons learned and future directions.

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II. RELATED WORK

The TIKL system [16] is perhaps the closest to the system we developed in our preliminary work. TIKL augments visual feedback with feedback from vibrotactile motors. Augmenting visual feedback with tactile feedback improved the learning of certain motions.

Navbelts, belts augmented by vibration motors, are a popular form of electronic travel aid for the blind. These devices were originally developed in the 1990s ([3], [24]) and are still popular with users. In [26], Spelmezan *et al.* studied the feasibility of providing vibrotactile feedback for whole-body motions.

Zheng and Morrell [30] designed a posture chair. Their system uses seven force sensors embedded in the chair to detect the user's posture and six vibrotactile motors to provide posture feedback. Vibrotactile feedback is rapidly gaining in popularity in the domains of sports, navigation, rehabilitation, gaming, and motor learning. Alakhone *et al.* [1] provide a recent survey of applications using vibrotactile feedback.

In virtual reality, much focus has been on complete physical experiences. Teaching pose or motion may be simpler – we do not need to recreate the complete experience, but only guide at critical points. One class of VR applications are used to train users in situational awareness. Examples of such systems include [23], used to train law enforcement personnel for hostage crises. A similar system, described in [6], trains users to evacuate a battleship in case of emergencies.

Another class of VR trains users with intelligent *agents*. Agents are virtual characters in the virtual environment that interact with the user and train them. Rickel and Johnson ([12],[22]) created an interactive agent STEVE (Soar Training Expert for Virtual Environments) to assist users with machine operation training.

Holden *et al.* ([17], [10]) describe a virtual-environment-based tracking system to augment conventional rehabilitation therapy. Piron *et al.* ([20], [21]) have applied a similar technique for upper-arm motion rehabilitation with encouraging results.

The *Just follow me* system [28] uses *ghost metaphors* with virtual-reality to teach users dance moves. A ghost metaphor is a virtual-reality image of a trainer (constructed from motion-capture data) that is displayed in front of the trainee, who is expected to imitate it. Hachimura *et al.* [7] developed a similar system using mixed-reality technology.

Motion training is an important part of rehabilitation following a stroke or neural injury. MIT-Manus [9] (and later generations of the same system) are examples of haptic devices that learns a particular action in a learning phase and guide the patients through the same motion. Volpe *et al.* [27] show encouraging results using the Manus robot in rehabilitation of patients following a stroke.

Exoskeletons are popular for rehabilitation applications. The Bionic research lab at University of California at Santa Cruz has developed a wide range of exoskeletons for the human arm. Their most detailed exoskeleton for the upper body allows the user to control a seven-degree-of-freedom human arm [19]. Other assisting systems such as [5] target the lower limbs with special emphasis on gait correction.

Some attempts have been made to leverage the power of virtual-reality systems for haptic feedback. Jack *et al.* [11] describe a novel rehabilitation approach where patients wear haptic gloves to perform predesigned tasks in a virtual world. Yokohoji *et al.* [29] designed a system (WYSIWYF) to provide haptic feedback in a virtual environment.

Alexander *et al.* [2] used simple, low-resolution video-based motion-capture to analyze the efficacy of exercise in the elderly. Mora *et al.* [18] have used motion-capture data for correcting body posture while playing the piano.

Johnson *et al.* [13] built a *sympathetic interface* to let users control the actions of an animated character. Their system captured the user's action using a plush toy embedded with wireless sensors such as accelerometers, magnetometers, and gyroscopes.

In a novel medical application, Lee *et al.* [15] estimated the gait parameters such as stance, swing, single support, and double support time of the gait cycle using accelerometers attached to the patient's ankles. Hesch *et al.* [8] used a pedometer, a walking cane, a three-degree-of-freedom gyroscope and a 2D laser scanner to guide a blind user in a known environment.

III. System Design

There are some fundamental differences between robots and humans from a controller's perspective. Humans have binocular vision, touch sensitive skin, ten fingers, compliant force control, and natural inverse kinematics. Our systems leverage human capacities for sensing and manipulating the environment. For example, the shirt-folding system (section IV-C) uses human abilities to naturally perform inverse kinematics and grasp cloth.

Conversely, due to lack of a "standard interface" human response to feedback is slow, error-prone, and unpredictable. Much of the contribution of the work is in a preliminary attempt to address these human limitations, by providing feedback that is detailed enough to enable users to accomplish the tasks, yet intuitive and simple enough for users to comply with it.

Hardware setup

Figure 1 shows an overview of the tracking system, the feedback system, and the controller. The tracking devices provide the controller with the user's current state. Based on the user's state the controller calculates the appropriate feedback and conveys it to the feedback device. The user changes his state based on this feedback, and the system iterates until the user completes the motion task.

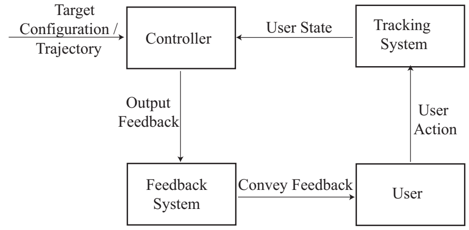


Fig. 1. System overview. The tracking system sends the current user state to the controller. The controller calculates the required feedback and sends it to the user, who changes state according to the feedback

We used a Vicon MX system running Vicon Nexus software to track users for configuration tasks. We used WiTilt v3 [25] modules as tracking sensors for trajectory tasks. WiTilts contain a three-axis accelerometer as their sensor. These sensors measure acceleration along three mutually orthogonal directions, and wirelessly transmit the sensor readings over a serial-over-Bluetooth connection using an RN-41 Bluetooth module. For tracking user's motion we mounted the WiTilts on the user's body.

We provide vibrotactile feedback using Lilypad vibration motors [4] that are mounted on the user. Based on the controller's instructions, some of these motors are switched on or off or pulsed. The user performs actions depending on the motors that are buzzing. The controller communicates with the feedback motors using communication devices. We used two communication devices for our applications: an Arduino BT microcontroller and XBee RF modules. The controllers are C++ applications that run on a Windows workstation.

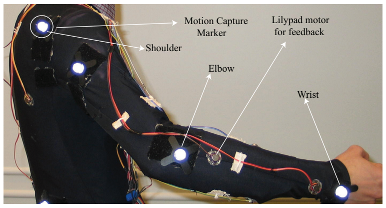
IV. Experiments and Results

For configuration tasks, the systems defines a set of motion primitives for the user. The choice of motion primitives depends on the task. An important characteristic for a motion primitive is that they are simple action that humans can easily perform. The complexity of a motion task is different from the complexity of the underlying motion. For example, walking is a complex motion that involves moving multiple joints and balancing the body's weight. However, a motion task defined as prompting a person to walk in a straight line may require only a simple motion controller.

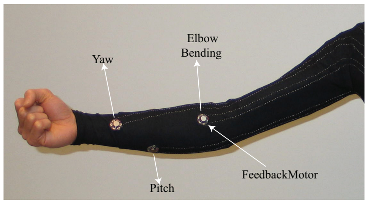
A. Mobile manipulation system

The mobile manipulation system allows a blindfolded user to navigate a room and manipulate objects. Such a system could be used as an aid to the visually impaired or provide task-based motion training.

The mobile manipulation system consists of two subsystems: the manipulation system and the navigation system. The manipulation system takes the target location (in world coordinates) as input, and guides the user's hand to the specified location. The navigation system guides the user to



(a) Manipulation system markers



(b) Manipulation system motors

Fig. 2. (a)Marker positions for the arm skeleton used by the posing system. (b) The placement of Lilypad motors on the arm for the manipulation system. Each of the motors shown here has a corresponding counterpart (not visible in this figure) to prompt the user to move in the opposite direction.

a target location and orientation, where orientation refers to the direction that the user is facing.

For both the navigation and manipulation subsystem, the user is restricted to a discrete set of predefined actions, the *motion primitives*. These motions are *natural* – they do not need complex training – and they depend on the task. Given a task, these systems prompt the user through a set of motion primitives that guide him to the target configuration.

The mobile manipulation system provides feedback using Lilypad [4] vibration motors. Two vibrating motors are typically used for each motion primitive. The motors are placed at locations that are intuitive for the particular action. For example, if the motion primitive is bending the elbow, a motor is placed near the elbow. When a motor buzzes, it signals the user to carry out the associated motion primitive. Restricted control implies that at any given time the system buzzes only one motor, simplifying the interpretation of feedback.

The manipulation system calculates the user's state by tracking the positions of four markers placed on the user's arm (figure 2(a)), and the user's shoulder acts as the origin of the body frame of reference for that arm. The configuration space variables for the system are the spherical polar coordinates for the hand, (r, θ, φ), where r is the distance from the origin, θ is the longitude, and φ is the colatitude. The mobile manipulation system relies on the human being to sense and grasp the object properly.

The motion primitives for the manipulation subsystems are three free rotations around joints: yaw and pitch rotation around the shoulder joint and the bending of the elbow joint. The navigation system utilizes two natural motion primitives: walk straight ahead, and turn in place. The walk-straight primitive needs one motor that prompts the user to walk straight ahead. The navigation system uses two motors for the turn-in-place primitive: one to indicate turning left and another to indicate turning right. The manipulation system typically enables the user to place the object within 1 cm of the target location.

The locomotion controller uses a simple "turn-drive-turn" algorithm. In the fist phase, the controller orients the user towards the target location, and then prompts him to walk straight towards it. Since the amount of turning and walking straight might not be precise, this phase may need multiple iterations till the user reaches the target location. Once at the target location, the user is prompted to turn in place until he is aligned with the target orientation. The navigation system is typically able to guide the user to within 15 cm of the target location and within 15° of the specified orientation.

B. *Arm-posing System*

We also developed a system that guides a four degree-of-freedom model of the arm to a specified pose. For the arm-posing system, a pose is specified with four joint angles: the yaw (θ), pitch (φ) and roll (β) for the shoulder joint, and the elbow bend (α). We ignore other degrees of freedom in the arm (two in the wrist and one in the forearm). The controller calculates the joint angles from motion-capture markers by solving the inverse kinematics equations for the arm. Based on the current and the target joint angles, the posing system directs the user through a set of motion primitives to achieve the target pose.

The motion primitives for this system are three natural rotations around the shoulder joint and the bending of the elbow. Each of these motion primitives changes the corresponding degree of freedom for the arm.

Figure 3 shows a set of images of successfully completed poses.

C. *Shirt-folding system*

We developed a system that guides a blindfolded user to fold a T-shirt. The shirt-folding system is more complex than other systems, and controls two arms using restricted feedback. The shirt-folding system combines some basic motion primitive into high-level motion tasks, and uses a sequence of such motion tasks for folding a T-shirt.

The shirt folding system uses the Cartesian coordinates of one fingertip on each arm to represent the system's state. The feedback motors are placed on the user's upper arm and forearm. The motion primitives correspond to moving the arm along three orthogonal directions (up/down, forward/backward and left/right).

We further defined a set of high-level motion tasks by combining these simple motions. Each high-level motion task involves moving the arm(s) to follow a particular sequence of motion primitives. Some of these high-level motion tasks involve moving both arms simultaneously. Each step in the shirt-folding process is achieved using one high-level motion task. The high-level motion tasks include *place one hand*, *move arms in parallel*, and *lay-down*, an alternation of downwards and forward motions that causes the user to spread the-shirt on the table while lowering it.

A Vicon MX motion-capture system tracked an 11-marker skeleton of the user's arms and torso. This system used 12

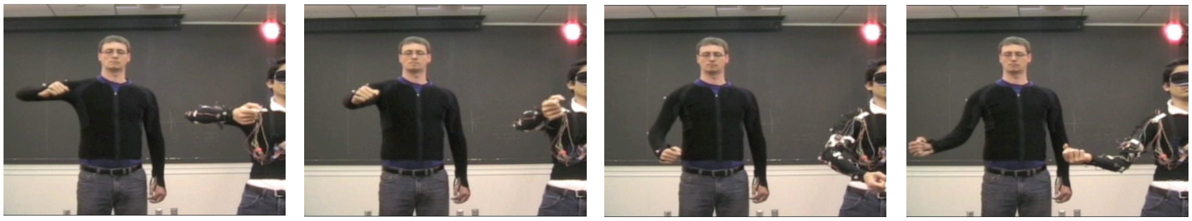


Fig. 3. The posing system guides the blindfolded user to copy the poses assumed by the second user. The actor on the left assumes a pose, and the blindfolded actor on the right is prompted to copy it. These images show a set of four successive poses.

motors (six on each arm) to provide feedback. Every motor corresponded to one particular motion primitive (either in positive or negative direction along a canonical axis).

Figure 4 shows a sequence of figures from one run of a user folding a T-shirt. Users were able to consistently fold the T-shirt using the system's feedback, and the average time for the fold was between two and three minutes.

D. Posture Shirt

Many human tasks require people to maintain a fixed posture. For example, it is important for piano players to maintain good posture while playing (see Mora *et al.* [18]). People working at a desk for extended durations are often advised to maintain a *good* posture to avoid problems such as chronic back aches. In the absence of external feedback, many people slowly drift from a good posture to a bad one, without noticing the change.

The posture system tracks the inclination of the user's upper back along two axes: one running along the waist, and the other parallel to the ground and perpendicular to the first axis. We refer to the rotation around the first axis (running along the waist) as the *bend* in the user's torso, and the inclination along the second axis as the *lean*.The posture system defines an ideal state and acceptable thresholds around the ideal state. If the user strays beyond these thresholds, he is prompted to correct his posture.

We conducted the experiment on ten volunteers. Before starting the experiments, the researcher explained the goals of the experiment and the details of the tracking and feedback devices to the users. The experiment consisted of two parts, each lasting ten minutes. In the first part, the system measured the user's torso's orientation without providing feedback. In the second part, in addition to tracking the user's orientation, the posture system provided feedback to confine users to the desired target orientation.

Experiments used a δ value of three seconds and a timeout duration of five seconds before restarting the feedback loop, and a threshold value of $15°$ for bending the body in any of four cardinal directions.

Figure 5 shows the results of the posture system for one user. The two green and yellow horizontal lines correspond to the bending and leaning thresholds for the user. Ideally, the user's bending and leaning values must remain between these two horizontal lines. The blue and black curves in the graphs correspond to the user's bending and leaning angles measured by the sensor. The pink portion of these curves corresponds to periods when the user was not in an acceptable orientation.

It is clear from figures 5(a) and figure 5(b) that the user strayed beyond the acceptable threshold significantly more without feedback. In figure 5(b), within a short time of straying over the threshold the user returned to an acceptable configuration. For all ten users, figure 5(c) shows the percentage of time the users were sitting in a bad posture both with and without feedback. The black curves in figure 5(c) (corresponding to the feedback case) is significantly below the blue curves (corresponding to the case with no feedback).

E. Arm Motion System

We tested the arm-motion-feedback system for a simple repetitive arm motion. The elbow joint was the active degree of freedomthat bends/extends the elbow joint. This motion is similar to an arm-curl in weight lifting. The shoulder joint was the constrained degree of freedom, where the goal was to keep the upper arm parallel to the ground. The motion involved performing two motion segments sequentially. The first motion segment involved extending the forearm so that the bend in the elbow joint was $150°$. The second motion segment involved bending the elbow joint until the bend was $90°$[1]. These angles are *natural* angles, and so they are easy for the users to understand. The waiting time between the two segments was three seconds. The associated background task was to maintain the upper arm parallel to the ground. This background task prevents the upper arm from *dropping* while performing arm exercises.

The complete specification for the task could be stated as: bend/extend the arm till the target configuration, hold the pose for three seconds and maintain the upper arm in a horizontal position all through the motion. We evaluated the system on all three aspects of the motion: accuracy of the foreground task, maintaining form for the background task, and holding the pose for the correct duration between tasks.

WiTilts [25] were used to track the user's arm configuration. The WiTilts were mounted on the user's upper arm and forearm to track the two segments. WiTilts provide accurate acceleration data about their three axes, but this data is noisy. This noise causes spikes in the acceleration values, even when the underlying motion is smooth. We used a low-pass filter with weighted average over a history window.

[1]A fully extended forearm makes an angle of $180°$ and a fully bent forearm makes an angle of $0°$.

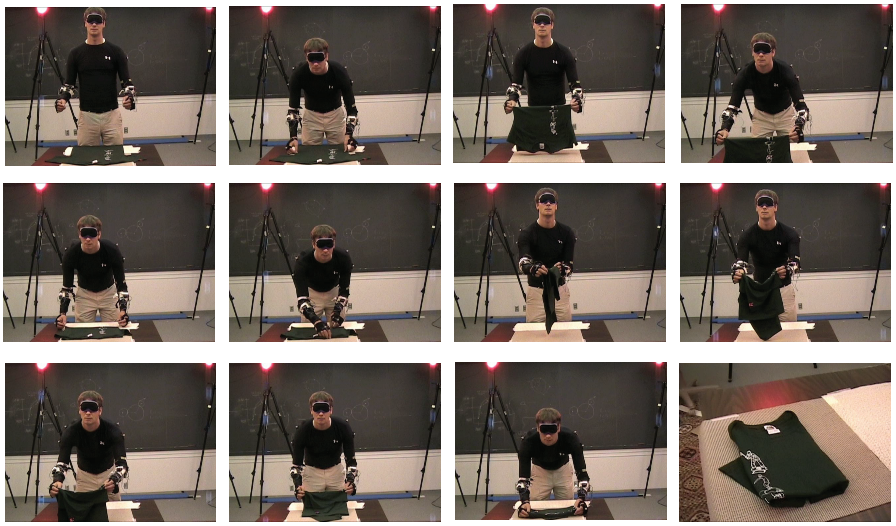
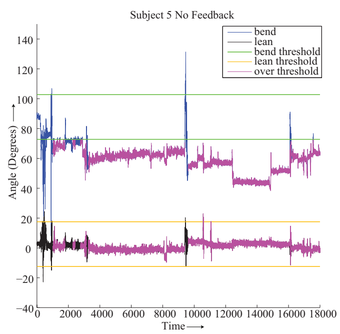
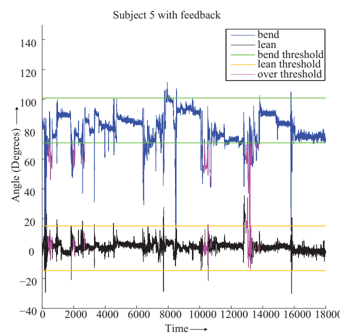


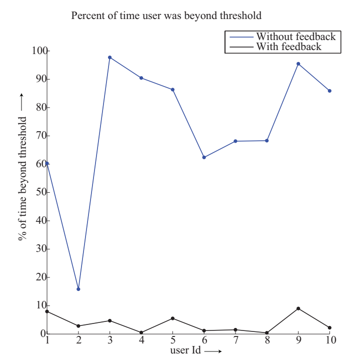
Fig. 4. Different steps involved in folding a T-shirt. Our systems guides a blindfolded user through a sequence of manipulation moves that fold the T-shirt. Note: not all moves are shown in this figure.



(a) User data without feedback

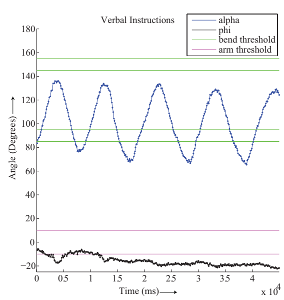


(b) User data with feedback

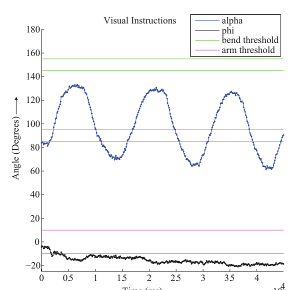


(c) Aggregate User data

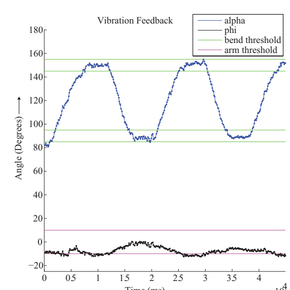
Fig. 5. Example results for one subject using the posture system. (a) User's posture data without feedback. (b) User's posture data with feedback. The portions where the user strayed beyond the threshold is shown in pink. The green and yellow lines show the threshold values for the bending and leaning of the torso. Ideally, the user should stay between those lines at all times. (c)Aggregate results for all ten users. The blue curve shows the percentage of time a user strayed beyond the permitted threshold without any feedback. The black curve shows the percentage of time the user strayed beyond the threshold using the feedback system.



(a) Verbal instruction 1



(b) Visual instruction 1

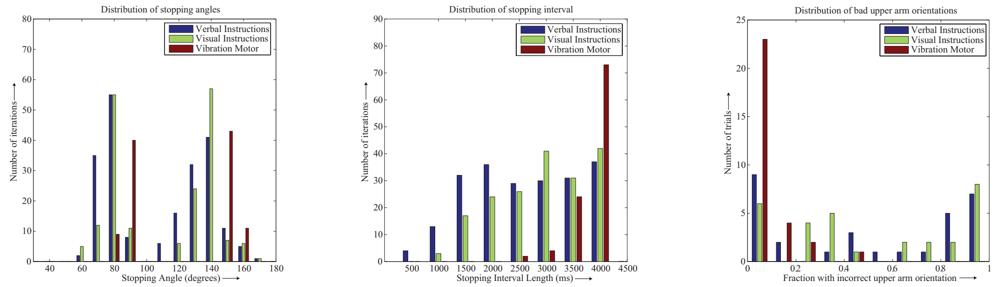


(c) Vibration Motor Feedback 1

Fig. 6. Examples of arm motion under different feedback conditions. (a) No feedback, only verbal description. (b) Visual instructions from watching an example video. (c) Vibration feedback with my system. All figures are from the same subject. α refers to the bend in the elbow and φ refers to the elevation of the upper arm. The green horizontal lines show the tolerated threshold for the error in the elbow bend, and the magenta lines show the tolerated threshold for the upper arm elevation.

We tested the arm-motion feedback system on 10 volunteers. Every volunteer was asked to perform the motion under one of three different conditons: with *verbal instructions*, with *visual instructions* (a video of the expected motion), and with *vibration feedback*. For each of the three feedback cases, each user was asked to perform the motion three times. Each of these trials lasted 45 seconds.

Figure 6 shows the results from one trial for one user



(a) Histograms showing the termination conditions for the foreground tasks for the three modes of feedback.

(b) Histograms showing the length of the waiting periods between foreground tasks for the three modes of feedback.

(c) Distribution of the fraction of time the background constraint was violated.

Fig. 7. Histograms showing the aggregate results over all trials under the three feedback conditions (a) Termination angle for foreground tasks. (b) Waiting interval when the termination condition is achieved. (c) Fraction of time the background constraint was violated.

with verbal instructions (figures 6(a)), visual instructions (figure 6(b)), and vibration feedback (figures 6(c)). In these figures, α refers to the bend in the elbow joint and φ refers to the elevation of the upper arm. The yellow and magenta horizontal lines represent the error threshold around the target configurations for the foreground and background tasks respectively.

Figure 6(c) shows the user's performance when provided with vibration feedback. The user performs the task accurately. For the foreground tasks, the user's target configurations lie between the yellow line. The upper arm's elevation mostly remains within the threshold for the background task. The waiting interval between the successive tasks is consistent and closer to the desired value (three seconds) than for other modes of feedback.

The examples shown in figure 6 are representative of the general performance for the three experimental conditions. For every trial, it is easy to calculate the fraction of observations where the background constraint was violated. Figure 7(c) plots a bar graph for the fraction of times the background constraint was violated. For vibration feedback, most trials have a small (less than 10%) fraction of observations where the background constraint was violated. Both visual instruction and verbal instructions systems show an almost uniform distribution for the fraction of observations that violated the background constraint. These results show that real-time feedback was effective in assisting users to observe the background constraint.

Figure 7 compares the results of the three methods for the foreground tasks. Both verbal- and visual-instructions systems show a large spread in the termination angle and the waiting intervals between foreground tasks. On the other hand, the terminating angle for vibration feedback shows two sharp peaks at 150°and 90°, the terminating conditions defined by our task descriptions. Also, the waiting time between foreground tasks show a sharp peak around 4000 ms and rapidly decrease; users showed small variance in their waiting time when they were provided vibration feedback. This implies that my system prompts users to wait for a consistent duration. The wait time of 4000 ms is, however, slightly longer that the 3000 ms specified by the tasks. In summary, the arm-motion feedback system provided effective feedback for all three aspects of the motion: accuracy, timing and form. This system was able to elicit uniform performance across users, as shown by sharp peaks in the distributions for the three motion metrics.

F. Motion Synchronization

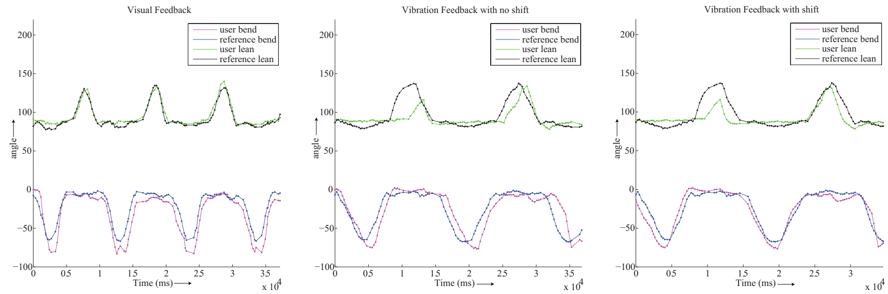
Human beings need to synchronize actions for many applications: rowing as part of a crew, dancing as a troupe, synchronized swimming, tug-of-war, etc. Actions need synchronizing in many different contexts, each with their own challenges and objectives. For example, in rowing and tug-of-war all actors need to apply force at the same time. On the other hand, dancers in a troupe need to execute their actions in the proper sequence with precise timing.

We have built a motion-synchronization system that synchronizes two users. Our system concentrates on one particular application: synchronizing the motion of two actors where one acts as a leader and the other as a follower. The actors cannot see each other, and the feedback from vibration motors is the only external cue to synchronize their motion. Further, only the follower receives feedback to match the leader. The motion-synchronization system has two users: a leader and a follower.

Similar to section IV-E, we consider repetitive motions that are composed of motion segments. While performing a motion sequence, at any instant a user is performing one particular motion segment. The leader's motion was a periodic torso motion with four segments: lean forward, lean backward, lean left, lean right. The system tracked both the users using WiTilt [25] three axes-accelerometers.

A vibration pulse buzzes the motors for δ ms (for some constant δ). The interval between two vibration pulses signifies the velocity of the motion.

Ideally, the pulse intervals should be varied continuously with the desired feedback. Practically, humans have a limited ability to distinguish between very similar pulse intervals, especially when the intervals are small (measured in milliseconds). Our system provides feedback with four different vibration intervals: 75ms, 150ms, 300ms, 600ms. The feedback provided using these intervals is ordinal; it

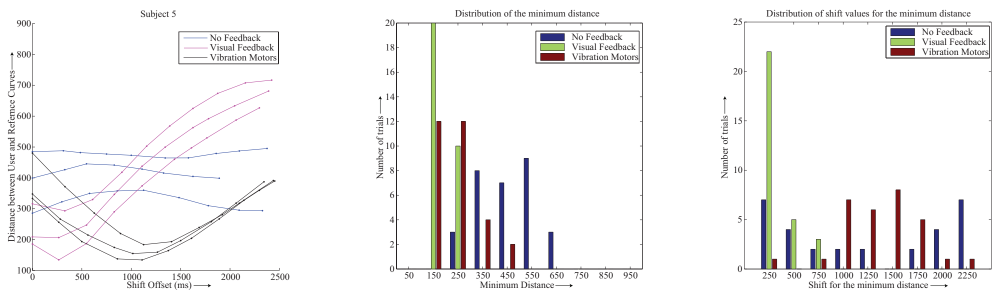


(a) Visual Feedback

(b) Feedback from vibration motors

(c) The user reference curve in figure 8(b) shifted to the left to align it with the reference curve

Fig. 8. Examples of user vs reference trajectories (a) visual feedback (b)vibration feedback. (c) The user curve shifted to achieve optimal alignment between the user and reference curves in figure 8(b).



(a) shift value vs distance between the curves

(b) A histogram of minimum distance between the curves for all runs from all users for the three different types of feedback.

(c) A histogram of shift needed to the user curve to achieve the minimum distance between the curves.

Fig. 9. (a)The change in distance between the two curves for a user for all three runs for the different feedback methods. (b) The minimum distance for all runs for the three modes of feedback. (c) The shift (in ms) needed to optimally align the user curve with the reference curves for all runs for all runs across all users.

prompts users to move *faster* or *slower* relative to their current velocity, but does not convey by how much.

The controller provides appropriate corrective feedback based on the leader's and follower's states. The controller performs three major functions. First, the controller interprets raw sensor data and calculates the orientations for both users. Based on the orientation and it infers the motion segments that both the users are executing. They may not be on the same motion segment. Finally, it calculates the appropriate action and velocity feedback for the follower. Each of these three functions is non-trivial, requires many design decision and a significant work to implement correctly. Interested readers can find details in [14]. We will present the experimental results here.

We tested the system on 10 volunteers. Before the experiment, the researcher described the motion to the volunteers, and showed them an example of the expected motion. The volunteers acted as followers, and followed a leader, under three separate sets of conditions: no feedback (although both leader and follower had previously practiced the motion), visual feedback, so that the follower could see the leader, and vibration feedback.

For each of the three feedback modes, every volunteer was asked to repeat the experiment three times. Every run of the experiment lasted 45 seconds. Both the leader and the follower were calibrated before every run. The leader was blindfolded during all feedback modes to prevent him from synchronizing with the follower.

Figure 8 shows the results of one example run each for visual and vibration feedback. Figure 8(a) shows the results for the case when the follower could see the reference. As expected, the follower could accurately and closely follow the leader. Such a close matching of the leader's trajectory may not be possible for more complex actions. Figure 8(b) shows the follower's performance in response to the vibration feedback that the motion-synchronization system provides. The follower's curve appears *shifted* to the right with respect to that of the leader. This lag is a combination of at least three different factors: lag in inferring a change in the leader's state, lag in conveying the feedback, and the lag introduced by the user in understanding and acting on the feedback. Figure 8(c) shows the follower's curve shifted to the left to align with the leader's curve. Such a shift compensates for the lag introduced by various factors described above. The amount of shift needed for the best alignment provides an estimate of the total lag present in the system.

The areas between the users' curves serves as a measure of distance between these curves. As the follower's curve is shifted, the distance between the leader's and follower's curve changes. At some value of the shift this distance becomes minimum. The minimum distance between the two curves provides a measure of how well the system performs when corrected for lag.

Figure 9 shows the aggregate results for all the users for all the modes of feedback. The minimum distance and the shift needed to achieve the minimum distance are small for visual feedback. For vibration feedback,the distance between the curves is small for the optimal alignment. The shifts needed to optimally align the curves mostly fall in the 1000ms to 1500 ms range. In contrast, both the minimum distance and shift values do not show any clustering when the follower was not provided any feedback. Details of our techniques for analyzing the results and feedback lag is presented in [14]

V. Conclusion

Many practical, everyday tasks can benefit from real time motion-feedback systems. Cheaper, accurate and more portable sensors and computing platforms such as smart phones will make it much easier to build such systems. We have made a first attempt at addressing the problem for delivering motion feedback for several useful everyday tasks. Our results with users are promising and promise great potential for such systems.

References

[1] A.U. Alahakone and S.M.N.A. Senanayake. Vibrotactile feedback systems: Current trends in rehabilitation, sports and information display. In *Advanced Intelligent Mechatronics, 2009. IEEE/ASME International Conference on*, pages 1148 –1153, July 2009.

[2] G. Alexander, T. Havens, M. Skubic, M. Rantz, J. Keller, and Abbott C. Markerless human motion capture-based exercise feedback system to increase efficacy and safety of elder exercise routines. *Gerontechnology*, 7(3):67, May 2008.

[3] J. Borenstein. The navbelt - a computerized multi-sensor travel aid for active guidance of the blind. In *CSUN's Fifth Annual Conference on Technology and Persons with Disabilities*, pages 107–116, 1990.

[4] L. Buechley. A construction kit for electronic textiles. In *Wearable Computers, 2006 10th IEEE International Symposium on*, pages 83–90, Oct. 2006.

[5] A. Cullell, J.C. Moreno, and J.L. Pons. The Gait Orthosis. A robotic system for functional compensation and biomechanical evaluation. In *Robotics and Automation, 2007 IEEE International Conference on*, pages 3136 –3137, April 2007.

[6] S. S. Everett, Wauchope K., and M. A. Prez Quiones. Creating natural language interfaces to VR systems. *Virtual Reality*, 4(2):103–113, 1999.

[7] K. Hachimura, H. Kato, and H. Tamura. A prototype dance training support system with motion capture and mixed reality technologies. In *Robot and Human Interactive Communication, 2004. 13th IEEE International Workshop on*, pages 217–222, Sept. 2004.

[8] Joel A. Hesch and Stergios I. Roumeliotis. Design and analysis of a portable indoor localization aid for the visually impaired. *International Journal of Robotics Research*, 29(11):1400–1415, Sept. 2010.

[9] N. Hogan, H.I. Krebs, J. Charnnarong, P. Srikrishna, and A. Sharon. MIT-MANUS: a workstation for manual therapy and training. In *Robot and Human Communication, 1992. Proceedings., IEEE International Workshop on Robot and Human Communication*, pages 161–165, Sept. 1992.

[10] M.K. Holden, T.A. Dyar, and L. Dayan-Cimadoro. Telerehabilitation using a virtual environment improves upper extremity function in patients with stroke. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 15(1):36–42, March 2007.

[11] D. Jack, R. Boian, A.S. Merians, M. Tremaine, G.C. Burdea, S.V. Adamovich, M. Recce, and H. Poizner. Virtual reality-enhanced stroke rehabilitation. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 9(3):308–318, Sept. 2001.

[12] Lewis Johnson, Jeff Rickel, Randy Stiles, and Allen Munro. Integrating pedagogical agents into virtual environments. *Presence: Teleoperators and Virtual Environment*, 7:523–546, 1998.

[13] Michael Patrick Johnson, Andrew D. Wilson, Bruce Blumberg, Christopher Kline, and Aaron F. Bobick. Sympathetic interfaces: Using a plush toy to direct synthetic characters. In *ACM SIGCHI Conference on Human Factors in Computing Systems*, pages 152–158, 1999.

[14] Paritosh A. Kavathekar. Assisting Human Motion-Tasks with Minimal, Real-time Feedback . Technical Report TR2011-695, Dartmouth College, Computer Science, Hanover, NH, June 2011.

[15] Jung-Ah Lee, Sang-Hyun Cho, Jeong-Whan Lee, Kang-Hwi Lee, and Heui-Kyung Yang. Wearable accelerometer system for measuring the temporal parameters of gait. *Conf Proc IEEE Eng Med Biol Soc*, 2007:483–6, 2007.

[16] J.. Lieberman and C.. Breazeal. Tikl: Development of a wearable vibrotactile feedback suit for improved human motor learning. *IEEE Transactions on Robotics*, 23(5):919–926, Oct. 2007.

[17] Holden Maureen, Todorov Emanuel, Callahan Janet, and Bizzi Emilio. Virtual environment training improves motor performance in two patients with stroke: Case report. *Journal of Neurologic Physical Therapy*, 23(2):57–67, May 1999.

[18] Javier Mora, Won-Sook Lee, and Gilles Comeau. 3D visual feedback in learning of piano posture. In *Technologies for E-Learning and Digital Entertainment*, volume 4469 of *Lecture Notes in Computer Science*, pages 763–771. Springer Berlin / Heidelberg, 2007.

[19] J.C. Perry, J. Rosen, and S. Burns. Upper-limb powered exoskeleton design. *Mechatronics, IEEE/ASME Transactions on*, 12(4):408 –417, Aug. 2007.

[20] L. Piron, P. Tonin, F. Cortese, M. Zampolini, F. Piccione, M. Agostini, C. Zucconi, A. Turolla, and M. Dam. Post-stroke arm motor telerehabilitation web-based. In *Virtual Rehabilitation, 2006 International Workshop on*, pages 145–148, 0-0 2006.

[21] Lamberto Piron, Paolo Tombolini, Andrea Turolla, Carla Zucconi, Michela Agostini, Mauro Dam, Giovanna Santarello, Francesco Piccione, and Paolo Tonin. Reinforced feedback in virtual environment facilitates the arm motor recovery in patients after a recent stroke. In *Virtual Rehabilitation, 2007*, pages 121–123, Sept. 2007.

[22] Jeff Rickel and W. Lewis Johnson. Animated agents for procedural training in virtual reality: Perception, cognition, and motor control. *Applied Artificial Intelligence*, 13:343–382, 1998.

[23] D.M. Shawver. Virtual actors and avatars in a flexible user-determined-scenario environment. In *Proceedings of IEEE VRAIS*, pages 170–177, 1997.

[24] Shraga Shoval, Johann Borenstein, and Yoram Koren. Auditory guidance with the navbelt - a computerized travel aid for the blind. *IEEE Transactions on Systems, Man, and Cybernetics*, 28:459–467, 1998.

[25] Sparkfun Electronics, 6175 Longbow Drive, Suit 200, Boulder Colorado, USA. *WiTilt v3*.

[26] Daniel Spelmezan, Mareike Jacobs, Anke Hilgers, and Jan Borchers. Tactile motion instructions for physical activities. In *Proceedings of the 27th international conference on Human factors in computing systems*, CHI '09, pages 2243–2252, New York, NY, USA, 2009. ACM.

[27] BT Volpe, HI Krebs, N Hogan, OTR L Edelstein, C Diels, and M Aisen. A novel approach to stroke rehabilitation: robot-aided sensorimotor stimulation. *Neurology*, 54(12):1938–1944, May 2000.

[28] Ungyeon Yang and Gerard Jounghyun Kim. Implementation and evaluation of "just follow me": an immersive, VR-based, motion-training system. *Presence: Teleoperators and Virtual Environments*, 11(3):304–323, 2002.

[29] Yasuyoshi Yokokohji, Ralph L. Hollis, and Takeo Kanade. WYSIWYF Display: A Visual/Haptic Interface to Virtual Environment. *Presence: Teleoperators and Virtual Environments*, 8(4):412–434, 1999.

[30] Ying Zheng and J.B. Morrell. A vibrotactile feedback approach to posture guidance. In *Haptics Symposium, 2010 IEEE*, pages 351 –358, Mar 2010.