Contribution of artificial proprioception on a dynamic finger flexion task

Mehdi HOJATMADANI1, Evren SAMUR2∗

1Department of Mechanical Engineering, College of Engineering, University of South Florida, Tampa, FL, USA
2Department of Mechanical Engineering, Faculty of Engineering, Boğaziçi University, İstanbul, Turkey

Abstract: There has been a considerable effort to provide sensory feedback for myoelectric prostheses. Among the solutions provided in the literature, sensory substitution is an easy and cost-effective way to provide feedback through different sensory modalities at different locations on the body. In this study, we evaluate the effect of sensory substitution of force and position feedback on a two-degree-of-freedom dynamic finger flexion task. For this purpose, a new methodology and an experimental setup are developed. The experimental methodology is based on the “strength-dexterity test”, working on the principle of buckling of compression springs. The experimental setup comprises a haptic interface, an input device, a force sensor, two vibration feedback tactors, and a virtual environment. A psychophysical test is conducted where subjects interact with a virtual spring with the index finger of their dominant hand through the haptic interface, the input device, or the force sensor in either isotonic or isometric mode. Three feedback conditions are tested: no sensory substitution, modality-matched sensory substitution, and modality-mismatched sensory substitution (through vibration). Sensory substitution feedback is provided on the subject’s contralateral arm. Results show that sensory substitution of force and position does not have a significant contribution to subjects’ performance in the proposed dynamic task.

Key words: Robotics, interaction, virtual environment, sensory feedback, proprioception

1. Introduction

Since people with amputation lack tactile and proprioceptive sensing, there has been considerable effort to provide this sensory information for upper-limb myoelectric prostheses to achieve coordinated movement [1]. Lack of an efficient sensory feedback system has caused these robotic prostheses to lose their popularity among users as they cannot reflect realistic feeling of performing a task. Dudkiewicz et al. [2] reported that the rejection rate in myoelectric prostheses was around 30%. The main reason for prosthesis rejection was dissatisfaction with prosthetic comfort, function, and control [3]. In spite of advances in prostheses development, the main problem of the lack of realistic sensory information still exists. Among the solutions provided in the literature [1], including neural interfaces [4, 5] and targeted muscle reinnervation [6–8], sensory substitution is an easy and cost-effective way to provide feedback through different sensory modalities at different locations on the body.

Proprioception plays an important role in body coordination during movements where multiple joints are involved [9–11]. Despite the benefits of proprioceptive feedback, only a limited number of studies have provided this feedback for upper-limb robotic prostheses [12–18]. In these studies, proprioceptive information was provided through sensory substitution, and users of such systems did not perform any better in prosthesis
control than with visual feedback alone [19, 20]. Therefore, sensory substitution of proprioception (artificial proprioception) is not adopted clinically. On the other hand, widely used body-powered prosthetic systems enable superior control in tasks of manual dexterity, partially due to extended physiological proprioception (EPP) [21]. A recent study showed that coupled input and feedback in a body-powered prosthesis also allows good object identification accuracy [22]. These results suggest that any method to provide sensory feedback for improved prosthesis control should be physiologically appropriate (e.g., same modality, collocated, high signal-to-noise ratio) in order to take advantage of proprioceptive reflexes and loops. We assume that this kind of feedback, where the user receives information through the same channel, in which the prosthesis is controlled (i.e., collocated actuation and sensing), would enable intuitive control while reducing mental load. However, it has not been investigated rigorously in literature whether physiologically appropriate proprioceptive feedback is necessary or artificial proprioception is adequate for improved performance in prosthesis control as compared to vision-only situations.

Few studies in literature investigated the effect of proprioceptive feedback on prosthesis control [20, 23–28]. These studies mainly focused on perception of either limb position or external object compliance, mostly through vibration [23–25]. Blank et al. [20] compared the benefits of visual and proprioceptive feedback on single-DOF targeted motion tasks. Their results indicated that targeting accuracy was elevated with proprioceptive feedback under all nonsighted conditions and some sighted conditions. In a study by Gurari et al. [26], stiffness discrimination with and without proprioception was investigated. Their results did not show a significant difference between visual and proprioceptive feedback modes, but subjects perceived proprioceptive feedback to be significantly more useful than visual feedback. Pistohl et al. [27] conducted a set of positioning experiments with a 2-DOF myoelectrically controlled computer interface. Participants were required to reach a target with the interface while they were provided with additional proprioceptive feedback. However, this artificial proprioceptive feedback did not increase the overall accuracy of the positioning task. More recently, Brown et al. [28] investigated whether artificial force and position feedback degrades the perception of virtual springs. They showed that compliance discrimination was degraded with noncollocated kinesthetic and vibrotactile feedback. Although these studies in the literature identified the role of proprioception to some extent, there is still a need to examine artificial proprioceptive feedback in a multi-DOF, dynamic scenario where position and force control tasks are not isolated.

Our objective in this study is to identify the relative contribution of artificial proprioception on the control of an unstable, 2-DOF virtual task. To do this, we have implemented virtual representation of compression of a spring that can buckle. Manipulation of unstable objects requires feedback control because this novel interaction is difficult to perform in an open-loop fashion. We suppose that action-sensing collocation plays an important role in successful completion of such manipulation tasks. Therefore, we hypothesize that sensory substitution in which feedback is not provided at the location of action is of little help for dynamic manipulations, especially when visual feedback is available. To test this hypothesis, we have developed a new methodology where artificial proprioception can be investigated in a virtual dynamic finger flexion task. In the following sections, the proposed methodology and the psychophysical experiments performed are presented.

2. Methodology

Control of powered upper-limb prostheses mostly relies on electromyography (EMG), which is an indirect estimator of muscle force. Corbett et al. [29] experimentally showed that isotonic input for position control of prostheses provided better tracking accuracy than EMG and force sensing, which require isometric contractions.
Similarly, studies with computer input devices for virtual environments showed that users’ performance in virtual object positioning is worse with isometric input devices than isotonic input ones when position control is employed \cite{30}. One of the reasons for this degradation is the lack of position feedback in isometric conditions. Considering this result, the approach in this study was to investigate whether able-bodied subjects perform better at a multi-DOF manipulation task with isometric and isotonic control when proprioceptive feedback is substituted.

The proposed methodology is based on the “strength-dexterity test”, where subjects were asked to compress a spring up to a certain point without buckling the spring \cite{31–33}. The strength-dexterity test was proposed for evaluation of proprioception since the involved task highly depends on coordination of force and position at the same time. We have adopted a virtual version of this test, so that it could be used as a method to validate artificial proprioception. Although the original task is a dynamic pinch, our implementation can be considered as an index finger flexion task. In the strength-dexterity test, subjects use a thumb to pinch a real spring. However, in our approach, the index finger interacts with a virtual spring. Therefore, the virtual task slightly differs from the original task. However, this virtual implementation provides a novel platform to test contributions of sensory feedback in 2-DOF dynamic manipulations. Implementing other hand gestures such as grasping or gripping instead of finger flexion would require incorporation of more fingers, and thus a more complicated situation would arise where contributions of various feedback methods could not be easily separated.

There are seven experimental modes comprising different input and sensory substitution feedback modalities. Each mode of the experiment is either isometric or isotonic, where participants will input position/force and will receive force/position feedback through modality-matched (force/position) or modality-mismatched (vibration) sensory substitution feedback.

2.1. Experimental setup

The experimental setup consists of a novel 2-DOF haptic interface, a 2-DOF input device, a 6-DOF force sensor, two vibration feedback tactors, and a virtual environment (Figure 1). Three light indicators (LEDs) were also employed to give subjects visual cues about different statuses of the task. The haptic device and the input device (Figure 2) have been designed to interface with the index finger. Their degrees of freedom are translation along the vertical axis (Y) and rotation around the sagittal axis (Z). Both devices have a workspace of 55 mm on the Y axis and 30 degrees around the Z axis, which have been specified based on human finger capabilities. While the input device has isotonic input capability, the force sensor is used as an isometric input device. The haptic interface is capable of providing position/force feedback.

2.1.1. Hardware
2.1.1.1. Haptic interface

The haptic interface is composed of a parallel mechanism, two DC motors with quadrature encoders (Maxon DCX22L and ENX 16 EASY), a series of joints (11 mm bearings), timing belts (Synchroflex T5/245), gears (20 mm), linear rails (Schneeberger Mn7), and a thimble (Figure 3a). Rotations of the motors are transmitted to translation and rotation of the thimble through belts, gears, and linear rails. The encoders have a resolution corresponding to translational resolution of 0.068 mm and rotational resolution of 0.16°. The motors are driven by two motor controllers (Pololu 18V7) for smooth operation. All high-level control commands are programmed in two Arduino Mega 2560 boards communicating with the PC via USB cables. The PC operating system
was Windows 7. Friction and gravity compensation algorithms are used so that users can have a transparent interaction with the virtual environment. Haptic loops are updated at a rate of 1000 Hz.

2.1.1.2. Input device

The input device comprises two encoders (OMRON E6B2), a brushed DC motor (Mitsumi Motor RS-540SH), and a thimble (Figure 3b). This 2-DOF device is kinematically analogous to the haptic interface with the only difference being that translation and rotation movements are decoupled, which results in considerably less friction. The haptic interface could have been designed identically to the input device as well. Although this would reduce friction in the haptic device, the added inertia due to the DC motor for rotational DOF would impede the performance of the haptic interface. The encoders used in the input device are relatively lighter than the DC motors, but weight and friction of the device are still compensated with the brushed DC motor operating at a constant load. The encoders are used to measure finger displacement, one for translational movement of the thimble and the second one for measuring its orientation. A pinion-and-rack mechanism guided on a linear rail is used to convert translation into rotation for measurement purposes.

2.1.1.3. Force sensor

An ATI Nano 17 force/torque sensor (calibration SI-50-0.5) is used as an isometric input device (Figure 3c). The force sensor is connected to the PC via an NI PCIe-6363 data acquisition card running with a sampling rate of 1000 Hz.
Figure 3. Schematic of interfaces used in the experiment: a) the haptic interface is an impedance-type device; b) the input device has isotonic input capability; c) the force sensor is used as an isometric input device.

Vibration feedback was delivered to subjects using two vibration feedback tactors. Each tactor was composed of two 12-mm vibration motors (Precision Microdrives Ltd.) mounted on top of each other as demonstrated on Figure 1. This method, which was proposed by Cipriani et al. [34], resulted in increased vibration intensity. Vibration amplitudes were modified by selectively activating the vibration motors. Vibration amplitudes were chosen such that they would be distinct and perceptible as well as not being distracting or overwhelming to subjects. Therefore, the midsection of the vibration motor performance range was chosen as the working range.

2.1.2. Virtual environment

We have developed a virtual spring model in the Simulation Open Framework Architecture (SOFA) platform, which is an Open GL-based graphical environment developed in C++. The spring is modeled as a deformable object composed of mechanical meshes. Mechanical properties of the virtual spring are selected in such a way as to resemble a real spring. The virtual spring is free to move in two DOF and both of its ends are constrained by virtual planes (i.e. end caps) to replicate boundary conditions of a real spring. The obtained scene is shown in Figure 4. The virtual environment loop is updated at 60 Hz.

For the simulation, we considered a compression spring \((K = 760 \text{ N/m})\) with the following design specifications: free length \(L = 76.2 \text{ mm}\), mean diameter \(D = 8.7 \text{ mm}\), wire diameter \(d = 0.79 \text{ mm}\), number of coils \(N = 24\), modulus of elasticity \(E = 210 \text{ GPa}\), Poisson ratio \(\nu = 0.313\), and material of music wire (\#12201, Century Spring Corp.). Considering that the spring is subjected to a bending moment \((M)\), we can...
obtain the following expression for the rotational spring constant by applying Castigilano’s theorem [35]:

\[
K_\theta = \frac{64DN_a}{Ed^4}(1 + \frac{\nu}{2}),
\]

(1)

where \(N_a\) is the number of active coils, which are not compressed completely and can deform. A realistic dynamic behavior is achieved by implementing the above relations.

\[ \text{Figure 4. A virtual spring controlled by the haptic interface in translation (along Y axis) and rotation (around Z axis) degrees of freedom.} \]

### 2.1.3. Buckling model

Buckling of the compression spring is examined by its resistance to bending. Venkadesan et al. [33] modeled the overall one-dimensional dynamics of a compression spring buckling system as a subcritical pitchfork bifurcation of the end cap angle \(\theta\) projected onto its first principal component, the compressive spring force \(F_s\). The derived formula can be described as:

\[
\dot{\theta} = \alpha(F_s - F_{\text{max}})\theta + \beta\theta^3 - \gamma\theta^5,
\]

(2)

where \(\dot{\theta}\) is the rate of change of angular position; \(\alpha\), \(\beta\), and \(\gamma\) are the stability model parameters [36]; and \(F_{\text{max}}\) represents the maximum attainable compressive spring force. The stability model parameters for this spring were selected as \(\alpha = 2.639\), \(\beta = 106.512\), \(\gamma = 385\), and \(F_{\text{max}} = 3.3\) N as in [33]. Considering negligible angular speed as compared to the other terms, and substituting these values into Eq. (2), we get:

\[
F_s = 145.88\theta^4 - 40.36\theta^2 + 3.3.
\]

(3)

The stability threshold is exceeded when the force applied to the end cap is more than or equal to the maximum attainable force \(F_s\), which is a function of the end cap angle \(\theta\). If the maximum attainable compressive force is exceeded, the spring buckles. Provided that the spring is compressed with zero angle, there is still a possibility of buckling. Since two critical factors in spring buckling are the end cap angle and applied force, both position and force of the virtual spring should be controlled simultaneously. Therefore, this unstable task highly depends on coordination of force and position.

### 2.2. Experimental protocol

Seven experimental modes were designed to determine the contribution of position and force feedback on manipulation of a virtual spring. Subjects were asked to compress the virtual spring with the index finger.
of their dominant hand through multiple devices (i.e. the haptic interface, input device, and force sensor) while they were receiving different sensory feedback. The task was to compress the virtual spring by a predetermined amount without letting it buckle. They were instructed to avoid any sudden and rapid movement. A scene from the experiments is shown in Figure 1. The Institutional Review Board of Boğaziçi University approved the experimental protocol.

2.2.1. Subjects

Fourteen healthy subjects (eight men, six women) who did not suffer from any motor disorders volunteered to participate in the study after reading and signing the consent form. They were recruited via advertisements on the campuses of Boğaziçi University. Twelve of them were right-handed. Prior to the experiment, there was a briefing session for each subject to explain the general objectives of the experiment and how to use each device in the experimental setup.

2.2.2. Procedure

Each experimental mode consisted of two parts: a training session and main session. In the training session, subjects were allowed to interact with the corresponding device until they met a certain learning condition, which was defined as three consecutive successful trials. The learning condition and number of trials were chosen such that subjects did not feel any fatigue in their fingers and did not lose their concentration due to length of experiment, as well as becoming adequately experienced in carrying out the experiment. At the end of each training session, subjects were asked to assign a number between one and five to each mode based on perceived difficulty of the task in that mode. One represented “very easy” and five represented “very difficult”. Following the training session, in the main session subjects performed 10 trials in each mode. The following parameters were recorded for both training and main sessions: whether the task was successfully completed or not, completion time in case of a successful trial, and failure time in case of an unsuccessful trial.

Subjects completed all experiment modes, which were randomly presented. They were seated on a chair looking at the screen to receive visual feedback from the virtual spring. The LEDs in front of the screen signaled the progress of each trial. Subjects began the task when a green light was on and had to compress the virtual spring until reaching the intended compression, which was 13 mm. Upon reaching the goal, the green light turned off and a red light switched on. The red light stayed on for 5 s, indicating subjects to keep the virtual spring in the same position. Subjects were informed about the completion of each trial by a yellow light. If they managed to complete the task without buckling the virtual spring, the task was considered successful.

2.2.3. Experimental modes

There were seven experimental modes, which contained different input and sensory substitution feedback. These modes are summarized in the Table. In order to facilitate analysis of the experimental results in the following sections, we have devised an abbreviation for each mode (e.g., PN for the second mode). The first letter represents input modality, which is either position (P) or force (F). The last letter represents modality of sensory substitution feedback, which can be vibration (V), force (F), position (P), or none (N). In the first three experiments, subjects did not receive any sensory substitution feedback. Therefore, these experiments set a baseline to analyze how well sensory substitution feedback improved subjects’ performances in completing the task. While the contribution of modality-mismatched sensory substitution was assessed in the fourth and fifth modes, the last two modes were designed to determine the effect of modality-matched sensory substitution.
Table. Different modes of the experiment.

<table>
<thead>
<tr>
<th>Modes</th>
<th>Procedure</th>
<th>Sensory substitution</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (PFN)</td>
<td>Subject compresses the virtual spring, and receives force and position feedback through the haptic interface.</td>
<td>None</td>
</tr>
<tr>
<td>2 (PN)</td>
<td>Subject compresses the virtual spring through the input device. No force feedback is provided.</td>
<td>None</td>
</tr>
<tr>
<td>3 (FN)</td>
<td>Subject compresses the virtual spring through the force sensor. No position feedback is provided.</td>
<td>None</td>
</tr>
<tr>
<td>4 (PV)</td>
<td>Subject compresses the virtual spring through the input device. Vibration feedback proportional to spring force is provided on the contralateral forearm.</td>
<td>Vibration</td>
</tr>
<tr>
<td>5 (FV)</td>
<td>Subject compresses the virtual spring through the force sensor. Vibration feedback proportional to spring compression is provided on the contralateral forearm.</td>
<td>Vibration</td>
</tr>
<tr>
<td>6 (PF)</td>
<td>Subject compresses the virtual spring through the input device. Force feedback is provided on the contralateral index finger through the haptic interface.</td>
<td>Force</td>
</tr>
<tr>
<td>7 (FP)</td>
<td>Subject compresses the virtual spring through the force sensor. Position feedback is provided on the contralateral index finger through the haptic interface.</td>
<td>Position</td>
</tr>
</tbody>
</table>

Please note that “P” is used to represent both translation along the Y axis and rotation around the Z axis. Similarly, “F” refers to force and torque in the corresponding degree of freedom.

As summarized in the Table, in the first mode (PFN), subjects interacted with the virtual spring via the haptic device providing spring force and torque proportional to the spring compression. Hence, they received both position and force feedback to the same hand. In the second mode (PN), subjects used the input device to compress the virtual spring without any force feedback. Since the finger was free to move, the input condition was isotonic. In the third mode (FN), subjects pressed on the force sensor, and resulting force and torque was applied to the virtual spring. In this case, the input condition was isometric since the input finger was stationary. In the fourth (PV) and fifth (FV) modes, the input conditions were the same as in the second and third modes, respectively. However, two additional vibration feedback modes, mapping the spring force and torque, or the end cap position and orientation, were delivered to subjects on their contralateral forearm. Vibrations were applied to the contralateral arm to be consistent with the sixth and seventh experimental modes. This was necessary for fair comparisons among the feedback types. Vibrations were delivered to subjects' glabrous skin 10 cm apart from each other. Compression or tilt of the virtual spring increased the amplitude of vibration feedback, representing force and torque, or position and orientation. The sixth mode (PF) resembled the second mode; however, subjects were asked to place their contralateral index finger on the haptic device. Here, subjects were instructed to keep their contralateral finger stationary while compressing the virtual spring with their dominant hand’s index finger via the input device. The haptic device applied force and torque feedback proportional to the spring compression. In the seventh mode (FP), position and orientation feedback was given to the contralateral index finger via the haptic device while subjects pressed on the force sensor with their dominant hand’s index finger. Subjects received visual feedback in all modes.
3. Results

All datasets were tested for normality in order to perform an ANOVA test. Normality conditions were met; hence, we utilized parametric statistical tools to analyze our data. Statistical analysis was performed on the experimental data with SPSS.

Analysis of subjects’ performance in the training session provides us with information about subjects’ learning processes. In this regard, we first analyzed the number of trials performed before accomplishing the learning condition in the training session. Mean values and standard errors of the number of trials among all subjects were calculated for each mode. The results are shown in Figure 5. In this figure, modes with position input are colored green, modes with force input are colored red, and the mode with both position and force inputs is colored blue. There was a statistically significant difference between modes as determined by one-way ANOVA (F(6, 91) = 4.362, P = 0.001). Tukey HSD post hoc analysis reported significant differences between PN and FN (P = 0.035), FN and PV (P = 0.007), and PV and FP (P = 0.016). Subjects performed significantly fewer trials in the PN and PV modes than in the FN mode. Similarly, the number of trials in PV was significantly lower than in FP.

![Figure 5. Number of trials in the training session. Mean of all subjects’ trials is shown for each mode. The modes with position input are colored green, the modes with force input are colored red, and the mode with both position and force inputs is colored blue. Error bars represent standard deviation among subjects. Asterisks indicate statistically significant different pairs (P < .05).](image1)

![Figure 6. Subject ratings on difficulty of the task in the training session. Means of all subjects’ ratings are shown with standard deviations. One represented “very easy” and five represented “very difficult”. There is no statistically significant difference between the modes.](image2)

Success rate is considered as a performance metric in the psychophysical test. Figure 7 shows mean success rates for each mode in the main session. One-way ANOVA showed significant differences between the success rates for the modes (F(6, 89) = 4.446, P = 0.001). Tukey HSD post hoc analysis reported significant differences between PN and FN (P = 0.015) and PN and PF (P = 0.015), as well as between PN and FP (P = 0.011). It can be seen that the highest rate of success was achieved in the PN mode (87%) and the lowest performances were recorded in the FN, PF, and FP modes (71%). Subjects’ performance in the PFN mode was in between that of PN and FN. While vibration feedback (PV and FV) did not have any significant contribution or deterioration on task completion, force feedback for isotonic input (PF) deteriorated subjects’ performance in comparison with no sensory substitution (PN).

Task duration for each successful trial was measured as well. Results are shown in Figure 8. One-way ANOVA did not result in any significant difference between the modes (F(6, 91) = 1.113, P = 0.361). Subjects spent approximately 15 s to complete the task in each mode.
4. Discussion

Subjects’ perception of task difficulty did not reveal any significant difference between the modes. On the other hand, the number of trials before accomplishing the learning condition (Figure 5) indicates that the second and fourth modes (PN and PV), where the input condition was isotonic, were significantly easier than the third mode (FN), requiring isometric input. Similarly, subjects performed significantly more trials with FP than PV. These results indicate that the task employed in this study, which was a 2-DOF targeting task in a dynamic environment, was easier to perform with an isotonic input device. Subjects learned much faster in the isotonic mode since proprioceptive feedback is naturally available. In the isometric modes, on the other hand, subjects should develop an internal mapping between applied force and resulting position change of the virtual spring cap.

The results also show that sensory substitution did not have any significant effect on learning of the task in this scenario. This means that substituting a missing feedback modality (e.g., position for the isometric input as in the FV and FP modes) does not make the task significantly easier than without substitution in this task. This conclusion is valid for both modality-matched and modality-mismatched conditions. However, the following trends must be noted, although they were not statistically significant. First, when the input was isometric, subjects learned faster with vibration feedback (FV) than without (FN) and with position feedback (FP). This is in agreement with the previous studies on sensory substitution of proprioception, suggesting that vibration feedback had a constructive effect on subjects’ task-learning performance [24, 26]. Second, the task was harder to learn with force feedback (PF) than without force feedback (PN) or with vibration feedback (PV) when the input was isotonic. It was as hard as in the FN and FP modes. These trends suggest that the additional position information through simple vibration helped learning of the 2-DOF task in the isometric condition. However, the way force feedback is substituted with the haptic interface made the task harder to learn in the isotonic condition. In the PF mode, subjects not only used their dominant hand’s index finger to control the input device, but also paid attention to their contralateral index finger to keep it stationary on the haptic device. This additional physical and cognitive load might have made the task more challenging.

For the main session, the results are presented in terms of success rate and time (see Figures 7 and 8). There was no significant difference in success time between different modes. However, the results of success rate show that subjects performed better with the isotonic input device (PN) than the isometric one (FN).
when there was no sensory substitution. This result is in line with the results of the training session. It is also consistent with the literature, showing that virtual object positioning is worse with isometric devices than isotonic ones because of lacking position feedback in isometric condition [30]. When the missing position feedback was substituted through vibration (FV), subjects performed as good as they did with the isotonic device (PN and PV). However, please note that FV is not significantly different than FN or FP. Therefore, we may infer that sensory substitution of position through vibration contributes slightly to completion of the 2-DOF task performed with visual feedback. On the other hand, addition of force feedback for isotonic input (PF) deteriorated subjects’ performance in comparison with no force feedback (PN). One reason why subjects could not perform well with the modality-matched sensory substitution could be the additional cognitive load, as discussed earlier. One can also argue that the task becomes merely a 2-DOF positioning task rather than a dynamic one in the isotonic modes, and thus additional force information is not necessary for controlling the virtual spring.

5. Conclusion

In this study, an experimental methodology to evaluate the effects of sensory substitution of force and position on an unstable, 2-DOF dynamic task has been proposed. A virtual model of the strength-dexterity test [31] has been implemented, in which subjects were asked to compress a 2-DOF virtual spring to a certain amount without buckling. Our approach differs from previous studies [20, 26–28] in terms of the employed task, which involves a dynamic manipulation in an unstable environment. This task requires both force and position feedback for successful manipulation. Therefore, the proposed virtual implementation provides a novel platform to test and quantify contributions of different sensory substitution systems to dynamic tasks requiring coordination of force and position.

There are some basic differences between the physical representation of the strength-dexterity test versus the virtual one proposed in this study. In the strength-dexterity test, subjects use a thumb to pinch a real spring. However, in our approach, the index finger interacts with a virtual spring. Therefore, the task might be considered as a finger flexion task rather than a pinch task.

Three different input devices and two sensory feedback methods were tested experimentally. The results showed that sensory substitution did not contribute significantly to successful completion of the proposed 2-DOF dynamic task where two different sensory substitution feedbacks were provided on the contralateral arm/hand in addition to visual feedback. This result supports our hypothesis that sensory substitution is of little help for dynamic manipulations when visual feedback is available. However, it should be noted that the modality-matched sensory substitution in this study required subjects’ considerable attention and was less intuitive, thus resulting in deterioration of subjects’ performance. On the other hand, the vibration feedback did not impose additional physical load on subjects and contributed positively to task completion. These results imply that additional task-relevant information, when provided in an unobstructed way, might help learning of similar tasks and slightly increase task completion performance. Therefore, future studies should focus on developing sensory substitution systems and methods that do not require active involvement in feedback delivery.

The following conditions should be taken into account when interpreting the results of this study. First of all, subjects were receiving visual feedback throughout the experiments. In a case where visual feedback is limited or completely eliminated, contribution of sensory substitution is expected to be increased. Similarly, if the experimental task is chosen to be more challenging by increasing DOF or by changing buckling properties, additional information through sensory substitution, which might not be obtained by vision, may have a critical
effect on task completion. Besides, if the artificial feedback is provided at a different location with a different strength or modality in a manner that is more readily incorporated into subjects’ sensory-motor system, it would be much more effective. Finding the right location of feedback delivery for each task and identifying the most intuitive sensory feedback form is still one of the challenges in the field. It is also worth mentioning that sensory substitution requires a significant amount of learning, which might be the reason for not obtaining significantly different performances. Evaluation of the impact of vibration amplitude on subjects’ performance and comfort level can also be investigated as an extension of this study. Finally, considering the fact that there was always a natural feedback (position or force) existing in all of the experimental modes, one might also argue that sensory substitution would have more impact when there is no sensory feedback at all, which is the case for people with amputation. Evaluating this hypothesis with users of robotic prostheses requires a different experimental setup since these users can control the virtual spring through different input methods such as EMG recordings. In order to test this hypothesis, the experiments could be performed with healthy subjects with the index finger anesthetized. This would block all tactile sensations but some of the kinesthetic feeling would be intact as the muscles of the finger span through the hand. This would still be a plausible condition to assume no physiological sensory feedback. However, all of these hypotheses need to be evaluated in a future study.

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