Laying the Groundwork for Intra-Robotic-Natural Limb Coordination: Is Fully Manual Control Viable?

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Supernumerary Robotic Limbs (SRLs) have been successfully applied in bracing and as an assistive technology for people with disabilities. These tasks only require perception internal to the SRL-human system. However, SRLs show promise in applications requiring external perception such as opening a door when one's hands are full. One path toward developing SRLs that accomplish these tasks is to use human-in-the-loop control, thus leveraging the human's superior perception system to help the SRLs. However, the effects on the user of controlling additional limbs are unclear. This article presents an experimental study where humans, wearing two single degree of freedom SRLs, were instructed to minimize the position error between the subject's natural and robotic limbs and the corresponding targets, one for each limb. First, subjects performed worse with their natural limbs when asked to perform the task with two natural and two robotic limbs as opposed to with just their natural limbs, suggesting that shared control could help. Second, subjects moved their natural limbs together followed by moving their SRLs together. This informs both the choice of control scheme for the SRLs and the division of labor within a task. Third, subjects showed significant concurrent use of the natural and robotic limbs.

CCS Concepts: • **Human-centered computing** → **User studies**; • **Computer systems organization** → **External interfaces for robotics**;

Additional Key Words and Phrases: Supernumerary robotic limbs

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1 INTRODUCTION

Wearable robotics research has traditionally focused on adding robotic devices in series or in parallel with the human users' natural limbs [14]. Advanced prosthetics, functioning in series, not only compensate for lost limb functions but also augment strength and enhance some functions of the missing limbs. Exoskeletons, functioning in parallel, increase joint torques and muscle strength

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with external actuators, or support a load with an elastic structure that stores energy and/or re-distributes the load across the body [3, 5].

Rather than mimicking the structure and kinematics of the human body, Supernumerary Robotic Limbs (SRLs) are a type of wearable robot that extend the human users' capabilities with extra robotic limbs attached to the human. Because they neither operate in series nor in parallel with the human's natural limbs, SRLs have the potential to broaden the functions a single human user can achieve by helping with holding, grasping, and manipulating objects, as well as supporting and bracing the human body [13, 19]. The MantisBot SRLs, for example, can brace the human body while the human is working on or near the floor [10]. The human does not have to use one of the natural arms to support the body; the SRLs support the body so that both human hands are available for a task. The SRLs on the shoulder can hold an object above the head while the human is fixing the object on the ceiling [4].

All of these examples of initial work within SRLs have focused on tasks that can be solved solely through measurements internal to the human-SRL system and using a leader-follower paradigm; measurements of the human, the leader, fully dictate the actions of the SRL, the follower. For example, the Supernumerary Robotic (SR) Fingers relied on measurement of the human's natural fingers to dictate the position of the SR Fingers [19]. Similarly, the robot on the shoulder used two Inertial Measurement Units (IMUs) to measure the actions of the human's wrists to dictate the robot's position [4]. However, SRLs show theoretical promise for tasks requiring perception external to the human-SRL system. Because of their portability, SRL could readily be integrated into household tasks such as adding seasoning during food preparation or opening a door when one's hands are full [11]. In fact, the recent Soft Poly-Limb (SPL) system demonstrated a soft robotic wearable arm operating a card swipe and opening a door for a user but relied on a secondary user to control the SPL [12]. Within manufacturing and assembly, SRLs could be used to help workers by operating secondary tools, grabbing parts from disparate areas and bringing them together for assembly, changing the orientation of objects during assembly, or holding cables out of the way during assembly. Broadly, barring a secondary operator to control the SRL, these tasks require concurrent and independent actions of the SRLs and the natural limbs and perception of objects external to the human-SRL system.

Traditional robotics might solve these problems by increasing the manual control of the robot. Placing the human in the loop leverages a human's superior perception/planning abilities to solve challenging external perception problems [18]. However, SRLs differ from traditional telerobotics in that ideally the user is able to operate both the natural body and the SRL concurrently. This both limits the choice for control inputs and increases the degrees of freedom (DOFs) the user must control. Direct teleoperation of a high-DOF robot with a low-dimension input device can lead to high cognitive and physical load [2]. Raising similar questions for SRLs, is there any limitation to exploiting extra wearable robotic limbs? Will users be able to take advantage of the extra DOFs offered by SRLs when given direct control over them?

Early related research into concurrent operation of SRLs and natural limbs on independent tasks is promising. In one study, users were given control of either two virtual hands that mirrored the movements of their natural hands or three virtual hands, two of which mirrored the movement of the natural hands and the third that mirrored the movement of their foot. When presented with three virtual falling objects, users preferred to use three virtual hands to catch the objects as compared to two virtual hands. However, no significant difference was found in success of catching the falling objects or in average effort during the tasks when comparing three virtual hands and two virtual hands [1].

Looking at the example tasks detailed previously, many of the tasks, such as adding seasoning to food or operating secondary tools, are currently done sequentially in the absence of SRLs. Thus,

Fig. 1. Experimental setup. (A) Subject showing the experimental setup and the SRL prototype. (B) Stage 1, where the subject moves to the targets with natural limbs (NL). (C) Stage 2, where the subject moves to the targets with the SRLs. (D) Stage 3, where the subject moves to the targets with both the NLs and the SRLs.

our goal is not simply to make an existing task easier by adding SRLs as previously studied, but to increase the number of actions that can be accomplished by the user concurrently.

In the current work, we aim to address whether a user can control both SRLs and the natural arms concurrently, as well as how the user coordinates the two tasks. To this end, we present a human study designed to explore how humans perform tasks that require concurrent actions, whether natural or robotic. We use simple but real physical SRLs attached to the subject's body. By designing the study to use a pair of natural limbs and a pair of SRLs, we can investigate both intra-robotic limb coordination and intra-robotic-natural limb coordination. The study occurred over multiple days to see if these results were stationary.

2 EXPERIMENTAL SETUP AND CONTROL SIGNAL

We conducted human subject experiments based on the protocol approved by the Massachusetts Institute of Technology Committee on the Use of Humans as Experimental Subjects (COUHES), #1604528486. All of the subjects ($N = 11$) were healthy, male, right-handed subjects, in good physical shape ($20 \leq \text{BMI} \leq 30$) and between 23 and 37 years old. The participants wore a prototype of the SRLs while standing in front of a set of four targets. See Figure 1(A). The goal of the subjects was to minimize the position error between the red disk-shaped targets and the position of the two robotic limbs and the two natural arms as the targets moved from position to position. Each limb, robotic and natural, was constrained to rotate about its base in the sagittal plane. In the case of the natural arms, this motion corresponds to the flexion/extension of the shoulder joint in a sagittal plane. Subjects were asked not to move their arms outside of this plane, extending them and keeping their elbow and wrist joints fixed; this meant that a change in the angle of the shoulder was directly reflected as a change in the angle of the hand. Thus, the shoulder angle could be tracked with an IMU held in hand of the subject.

The four targets were placed at the end of carbon fiber rods and moved with servomotors. The targets moved to a new, randomly generated position and held it for 15 seconds. The motions of the targets followed minimum-jerk trajectories [7] and lasted for 3 of the 15 seconds. The four target trajectories, having diverse step sizes and directions, are independent of each other. The experiment consisted of three stages. In stage 1, subjects did not wear the robot but simply followed the motion of two targets with their two natural arms (Figure 1(B)). In stage 2, subjects wore the

Fig. 2. Control architecture. The activation of the rectus abdominis on one side of the body rotates the corresponding robotic limb in the downward direction. The activation of the pectoralis major on the same side of the body rotates the corresponding robotic limb in the upward direction. This is analogous to an antagonistic arrangement of muscles.

robot and followed the motion of two targets with the two robotic limbs (Figure 1(C)). They were instructed to relax their natural arms. In stage 3, subjects wore the robot and followed the motion of the four targets using both natural and robotic limbs (Figure 1(D)).

Each subject participated in two experimental sessions for stage 1, three for stage 2, and another three for stage 3. Sessions consist of multiple trials of tracking, each lasting 3 minutes. Stage 1 and stage 3 sessions contained three trials each, whereas stage 2 sessions consisted of five trials. Subjects could rest between trials and could not participate in more than one session per day. In total, subjects spent roughly between 6 and 8 hours performing the experiment and 4.5 to 6 hours with the SRL; this is less than the total time required to perform the experiment, as they did not control the SRLs during stage 1.

Although not the focus of this article, the control scheme has an impact on the control experience of the subjects. For the purposes of this study, we sought a control scheme that did not interfere with the movement of the natural limbs and had previously demonstrated good performance on a task similar to stage 2 of this experiment—minimizing the position error between the SRL and a target. Given these requirements, we chose to use a previously studied control architecture [14]. In this previous work, the authors compared three different control strategies: position control, velocity control, and one based upon a muscle model. All of these control strategies used surface electromyography (sEMG) sensors placed on the pectoralis major and rectus abdominis muscles to get the subject’s control input. The authors asked their subjects to control two waist-mounted SRLs to minimize the error between targets and the SRLs as the targets moved from position to position. They found that the velocity control strategy led to the highest control performance, lowest user effort, and greatest independence from the natural limbs. Thus, although we make no claims of optimality of this control architecture, it satisfies our conditions as a control scheme.

The control architecture consisted of four sEMG sensors (make: Delsys, model: Bagnoli) that were attached to the pectoralis major (left and right) and rectus abdominis (left and right) muscles as shown in Figure 2. The muscle activation signals were acquired at a 250-Hz sampling rate, low-pass filtered (Butterworth filter, 2nd order, 10-Hz cutoff frequency), normalized (with maximum voluntary contraction values recorded at the beginning of every experimental session), rectified, clipped (between 0 and 1), and transformed into reference velocity commands for the robot’s

motors according to the velocity PI control law with gravity compensation

$$\tau = k_p(\dot{\theta}_{ref} - \dot{\theta}) + k_i \int_0^t (\dot{\theta}_{ref} - \dot{\theta}) du + g(\theta)$$

$$\dot{\theta}_{ref} = k_{EMG}(\alpha_{pos} - \alpha_{neg}).$$

Here, α_{pos} is generated by the pectoralis major and α_{neg} is produced by the rectus abdominis on the same side of the body as the robotic limb. The ratio of the gains is $\frac{k_p}{k_i} = 10$, and their values have been chosen to yield peak time $T_p = 0.5$. The control scheme is applied to each robotic limb separately. Note that as this control strategy repurposes the torso muscles for the control of the SRL, it is fundamentally a cannibalistic control strategy. However, as it operates in the null space of shoulder flexion and extension, it is not functionally cannibalistic in this context.

3 RESULTS

3.1 Raw Data

All of the subjects completed the three stages of tracking experiments. A sample of one subject's performance during one trial for each of the three stages is shown in Figure 3. Subjectively, the subject is able to quickly and accurately move the natural and robotic limbs as the targets move to each new position. To get a more holistic view of the subjects' performance, each trial was divided into 15-second segments that correspond to each target position. The subjects' responses were then normalized to move between 0 and 1, where 0 represents the beginning position at the 0-second mark and 1 represents the end position at the 15-second mark. These normalized trajectories appear similar to step responses for both the natural limbs and the SRLs.

3.2 Results on Performance

Typical performance metrics for a step responses are the absolute error at steady state and the rise time and as such were applied here. The absolute error at steady state was found for each target position as the absolute value of the difference between the position of the limb and the position of the target at the 15-second mark. The aggregated results are shown with the mean and 95% confidence interval in Figure 4(A). These results were also aggregated by trial and are shown with the mean and 95% confidence interval in Figure 4(C) and (D) for the natural limbs and SRLs, respectively. The rise time was calculated as 5% to 95% of the subject's trajectory in response to each target position. The aggregated results are shown with the mean and 95% confidence interval in Figure 4(B). These results were also aggregated by trial and are shown with the mean and 95% confidence interval in Figure 4(E) and (F) for the natural limbs and SRLs, respectively.

Unsurprisingly, the subjects achieved good performance in stage 1—using only the natural limbs—with a mean absolute error of 0.15 radians and a mean rise time of 2.78 seconds. During stage 2—using only the SRLs—subjects achieved a mean absolute error of 0.18 radians and a mean rise time of 4.20 seconds. During stage 3—using both sets of limbs—the subjects achieved a mean absolute error of 0.16 radians and a mean rise time of 3.79 seconds with their natural limbs and a mean absolute error of 0.18 and a mean rise time of 4.79 seconds with the SRLs. We believe that the fairly wide confidence intervals shown in Figure 4(C) through (F), and thus the fairly wide variability, is caused by variability in the task difficulty. Because the target's motions were random, it is likely that some sets of motions were easier than others. For example, if during stage 3 a subject were asked to move all four limbs up slightly, that would represent a relatively easy sets of motions. In contrast, a sets of motions requiring two limbs to move up and two limbs to move down would be relatively more difficult. Despite this variability, at the aggregated full stage level shown in Figure 4(A) and (B), the confidence interval bars become relatively narrow; this is due to

Fig. 3. Sample tracking. (A) Stage 1 trial: tracking of two targets with the human arms alone. (B) Stage 2 trial: tracking of two targets with the SRLs alone. (C) Stage 3 trial: simultaneous tracking of four targets with the human arms and the SRLs.

the large number of samples. This allows us to make meaningful statistical comparisons between stages on the performance of the subjects.

In addition, although these performance results are promising in that the subjects performed well with the SRL, it is important to note that the purpose of this study was not to demonstrate the effectiveness of the control architecture used but rather to investigate performance when adding limbs. As such, the performance shown here confirms the control architecture works well enough for our purposes; the subjects can readily complete the tasks given to them.

Fig. 4. Performance. (A, B) Aggregate results. Both panels include the four bars that represent the natural limb (NL) stage 1, SRL stage 2, NL stage 3, and SRL stage 3 performance, respectively. The error bars show the 5% to 95% confidence intervals. (C–F) NL absolute error, SRL absolute error, NL rise time, and SRL rise time, respectively. Each panel is divided into eight sections by the vertical lines, each representing a new session on a different day. The bolded vertical lines also split each panel into three sections, each representing a different stage of the experiment.

With these data, we can assess both performance within stages to see if subjects improved over time, suggesting learning, and between stages, to see if adding additional limbs with their own required actions affected performance of the original limbs on the original positioning task. First, to assess improvement within stages, we will compare the slope of the means of the data over all of the sessions within a stage, found by linear regression, to a slope of zero. Our null hypothesis is that there is no difference between the slope and zero, whereas the alternate hypothesis is that the slope is less than zero. Using this statistical test, we found that subjects showed no evidence of improvement during stage 1. During stage 2, subjects showed statistically significant improvement in terms of absolute error ($p < 0.05$) but not in terms of rise time. Finally, during stage 3, subjects showed statistically significant improvement with the SRLs in terms of absolute error ($p < 0.05$) and rise time ($p < 0.01$) but no statistically significant improvement with the natural limbs. In aggregate, these results suggest that subjects' performance with their natural limbs did not improve within either stage 1 or stage 3. This is expected; learning is unlikely to take place given the subjects' familiarity with positioning their natural limbs. Modest improvements were shown in stage 2, which again is to be expected; subjects' performance improved, at least in terms of rise time, as they became more familiar with the control scheme. Finally, subjects showed a fast rate of improvement during stage 3 with the SRLs, suggesting that, although not the purpose of this study, a longer study would have shown even better performance with the SRLs before plateauing.

It is important to note that if we apply the same statistical methodology with the null hypothesis being that there is no difference between the slope and zero while the alternate hypothesis is that the slope is greater than zero, we find that the subjects showed statistically significantly worse performance with the natural limbs as judged by rise time during stage 1 ($p < 0.05$). We believe that the reason for the performance degradation for natural limb rise time during stage 1 is a result of vigilance decrement, which has been shown to slow reaction times and increase error rates during tedious monitoring tasks and has been ascribed to under-arousal caused by an insufficient workload [16].

Next, we can assess how additional limbs affected performance. To do so, we will compare the two performance metrics, absolute error and rise time, between stages 1 and 3 for the natural limbs and between stages 2 and 3 for the SRLs. To do so, we used a one-sided two-sample t -test where the null hypothesis is that there is no difference in performance between the stages, whereas the alternate hypothesis is that subjects performed worse in stage 3 as compared to stage 1 for natural limbs and stage 2 for the SRLs. Subjects performed significantly worse with their natural limbs in stage 3 as compared to stage 1 with respect to both performance metrics (absolute error: $p < 0.05$, rise time: $p < 0.01$). Subjects also performed significantly worse with the SRLs in stage 3 as compared to stage 2 for rise time ($p < 0.01$) but not for absolute error.

On the surface, these results suggest that subjects performed worse when attempting to position all four limbs as compared to having to position only two limbs. However, it seems likely that, had the experiment continued, the subjects' performance in stage 3 with the SRLs may have not degraded as compared to stage 2 given the rapid improvement in stage 3 with the SRLs. This is in contrast to the subjects' performance with their natural limbs, which remained reasonably constant across stage 3. Thus, we can only safely conclude that adding additional robotic limbs degraded the performance of the subjects with their natural limbs over the course of the 8-day experiment.

3.3 Results on Concurrency

Looking closely at the normalized trajectories from stage 3 in Figure 4(A) and (B), it appears that there is an offset between when the natural limbs begin to move and the SRLs begin to move. To investigate this more closely, we plotted the two lines corresponding to each limb. The first

Fig. 5. Motion periods. NL1 and NL2 serve to distinguish between the two natural limbs, whereas SRL1 and SRL2 serve to distinguish between the two robotic limbs. Each limb has two lines associated with it. The earlier (lower) line represents the average time that that limb reached 5% of its final position, whereas the later (higher) line represents the average time that limb first reached 95% of its final position. The earlier line represents the beginning of the motion for each limb. On average, the natural limbs were activated first and concurrently followed by the SRLs being activated concurrently.

and second line represent the mean time at which a limb reached 5% and 95% of its final position, respectively (Figure 5). Roughly, the 5% line represents when the subjects started a movement with a limb. However, the 95% line does not necessarily represent when the subjects ended a movement, as many movements had a much longer settling time as shown by the trajectories in Figure 4(A) and (B). Within this figure, SRL1 and SRL2 serve to distinguish between the two robotic limbs, whereas NL1 and NL2 serve to distinguish between the two natural limbs. During stage 1, subjects' mean starting time with their natural limbs was 0.92 seconds for natural limb 1 and 0.93 seconds for natural limb 2. During stage 2, subjects' mean starting time with the SRLs was 1.56 seconds for SRL1 and 1.49 seconds for SRL2. Finally, during stage 3, subjects' mean starting time for natural limb 1, natural limb 2, SRL1, and SRL2 was 0.86, 0.85, 2.08, and 1.91 seconds, respectively. Using the same statistical test as we used to assess improvement in the performance metrics, we found no evidence that the starting time for any limb changed significantly over the course of a stage. However, using a one-sided two-sample t -test, we did find evidence that the starting time of the SRLs was later than the starting time of the natural limbs in stage 3 ($p < 0.01$). In aggregate, these results suggest that, on average, in stages 1 and 2, subjects tended to start the motion with their natural limbs and SRLs concurrently. In stage 3, on average, subjects first moved their natural limbs together followed by moving the SRLs together. Over the course of this experiment, all of these results were stationary.

Finally, Figure 6 shows the fraction of the time that all of the different limb groups were moving concurrently during the first 8 seconds of each new target position. This cutoff was chosen as it, on average, captures the limbs' movements during the time it takes to rise to 95% of the final settling value, as shown in Figure 5. During stage 1, the two natural limbs move concurrently 24% of the time, which is higher than the percentage of time that either natural limb was moving by itself. During stage 2, the two SRLs move concurrently 26% of the time. This is also higher than the percentage of time that either SRL was moving by itself. Finally, during stage 3, the two natural limbs move concurrently 20% of the time—accounting for times when one of the SRLs may have been also moving concurrently—and the two SRLs move concurrently 30% of the time, again accounting for times when one of the natural limbs may also have been moving concurrently. Interesting, both the natural limb–natural limb grouping and the SRL–SRL grouping are more common than

Fig. 6. Average limb group movement in each stage. Each color within the bars represents a different group of limbs that were moving simultaneously.

any natural limb–SRL grouping. However, all together, at least one natural limb and one SRL were moving concurrently 34% of the time. All four limbs were moved concurrently 4.3% of the time.

4 DISCUSSION

Although SRLs have been successfully applied to tasks that only require perception internal to the human–SRL system, such as bracing or as an assistive technology for people with disabilities, SRLs show theoretical promise in tasks that require perception external to the human–SRL system such as adding seasoning while cooking or operating secondary tools on the manufacturing floor. One attractive way to expand the task set that SRLs can be applied to is to insert humans into the loop and allow them to manually direct the SRL, thus leveraging the human’s superior perception. However, limited effort has been put forth to date to understanding the effect of adding additional limbs has on user performance. This study seeks to fill that gap by quantifying how subjects use physical SRLs during multi-limb concurrent and independent tasks.

First, we found evidence that subjects’ performance with their natural limbs degrades when subjects are asked to control all four limbs on concurrent, independent tasks as compared to when the subjects performed the task with only their natural limbs. Further, this effect did not diminish over the course of the multi-day experiment. This is perhaps unsurprising; much work has suggested that multi-tasking leads to increased error and longer execution times [15]. In adding additional concurrent actions required of the subjects, as was done during stage 3, less of their focus can be directed at the two natural limb targets. Even if the performance degradation we observed within this study were to dissipate with further practice, it is significant that the performance degradation exists, and was stationary, given the relative simplicity of the task—controlling four DOFS—and length of the 8-day experiment. We desire that SRLs offer immediate performance improvements rather than performance improvements with significant practice. Thus, it appears that SRLs would benefit from strategies developed by the shared control community to combat the difficulty of controlling many DOFs concurrently by attempting to seamlessly assist the user in completing the desire action with less control input.

It is unclear why the performance degradation that was found in the natural limbs during stage 3 was not also found in the SRLs. One hypothesis is that the improvement from learning to operate the SRLs counteracted the performance degradation typically associated with increasing the DOFs that had to be controlled, thus disguising the effect. Future work could investigate this by lengthening the study to reach a plateau in a subject’s performance with the SRLs.

Second, we found evidence that, at least within the context of this experiment, subjects responded first and simultaneously with their natural limbs followed by moving their SRLs

together. The reasoning for this is not a physical incapacity. As demonstrated in previous work, the EMG-based agonist-antagonist control scheme allows the subjects to operate the SRLs without causing motion of the natural limbs [14]. Further, we found that subjects did move all four limbs concurrently—4.3% of the time—during stage 3.

The observation of how subjects chose to respond to four concurrent and independent tasks can be leveraged in two ways. First, it can help inform the choice of control scheme for the SRLs. Interestingly enough, as noted in Section 1, many of the previous examples of SRLs have used a leader-follower control paradigm [10, 19]. Placing the human as the leader in this control paradigm is a natural application of this observation.

Beyond this, however, it informs which principles from shared control may be most successful for SRLs. In our experiment, we observed a time offset between when motion was initiated with the natural limbs as compared to the SRLs. Thus, one naive control scheme may be to divide the control of the SRL up temporally by initially attempting to automate the actions of the SRLs as the subjects move their natural limbs. After a brief time, control of the SRLs could be transferred to the human who could complete the fine positioning of the SRLs.

Second, this observation can help inform how to divide labor between the natural and robotic limbs during concurrent and independent tasks. Although not a perfect analogy, past work has shown that people tend to initiate movement with their dominant hand when presented with concurrent tasks, especially when the hands are not cooperating on the same object [6, 9]. Thus, in tasks that require concurrent robotic-natural limb action, the more time-sensitive task should be assigned to the natural limbs.

Finally, we found evidence that although the natural limbs were privileged, moving first and simultaneously followed by the robotic limbs, at least one natural limb and SRL were moved concurrently 34% of the time during stage 3. This suggests that the subjects did not simply break the task down into two sequential tasks to be operated on by each pair of limbs but rather partially combined the use of both the natural and robotic limbs.

We note that all of the findings of this article must be taken within the context of the controller choice. The particular muscles chosen here may not work well for women. This certainly opens the door for other muscle choices; the frontalis muscle on the forehead has been used to control a robotic sixth finger [17]. Further, the choice of a velocity controller is less bio-mimetic than other potential choices, as our limbs do not stop moving and hold position when our muscles stop firing. However, the control architecture chosen here allowed the subjects to perform sufficiently well with the SRLs on this particular task to allow comparisons in performance during multi-limb concurrent and independent tasks. Future studies could look at whether the findings here hold true for alternate control schemes. Additionally, future studies could investigate the effect of providing proprioceptive feedback to the subjects on the state of the SRLs; proprioceptive feedback has shown value in the prosthetics community [8].

5 CONCLUSION

We first found evidence that although subjects were able to move all four limbs concurrently, within the context of this experiment, there is a limit to exploiting wearable robotic limbs for additional concurrent tasks. Namely, we found that the subjects' performance with their natural limbs degraded as additional robotic limbs were added. Future work could investigate whether this performance degradation dissipates with practice; however, we desire that SRLs offer immediate benefits rather than require significant practice. This suggests that SRLs may benefit from drawing on control strategies from the shared control or other communities. Second, we found evidence that, within the context of this experiment, subjects generally moved their natural limbs prior to their robotic limbs. This suggests a leader-follower paradigm of control, where the SRL measures

the actions of the human and responds accordingly. Further, it informs how labor could be divided between the natural and robotic limbs. Specifically, it suggests giving the primary, more time-sensitive task to the natural limbs.

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