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Tri-manipulation: An evaluation of human performance in 3-handed teleoperation

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Abstract—With a third hand a human subject could possibly be able to perform tasks that they would otherwise be incapable of. Foot-controlled interfaces have proven suitable for controlling robot arms, however, when it is best to use such devices and what limitations they place when controlling a supernumerary robotic limb (SL) in combination with the natural limbs (NLs) is unknown. Here, we report an investigation of three-handed manipulation carried out using a foot interface. We analysed i) what effect the addition of SL has on the performance of the NLs; and ii) how mechanical and/or cognitive coupling alters user performance. When the subjects moved the three limbs without coupling, only the motion’s completion time was observed to be significantly affected. In contrast with coupling, the incorporation of the foot controlled hand was found to affect the success rate, and planning of the motion, however it did not affect motion characteristics such as smoothness.

Index Terms—Tri-manipulation, three-tools operation, foot control, teleoperation.

I. INTRODUCTION

Many teleoperation tasks require more than two instruments for successful completion. Currently, these tasks are executed by multiple people working together. For example, in endoscopic robotic surgery, the endoscope is handled by an assistant while the surgeon performs bi-manual operations. However, this can introduce communication errors [1], especially for a newly formed team or a novice assistant.

Using multi-modal interfaces may allow an operator to manipulate a SL independently of and in coordination with the NLs such that they can perform complex tasks without assistance. Hands-free control of teleoperated robots can use muscle [2] or motion signals [3]. Muscle interfaces can detect motion intention but their reliability suffers from noise and susceptibility to environmental disturbances [4]. Motion-based control is more reliable and accurate and therefore is the more commonly used interface for teleoperation.

The human body provides various possible motion-based human machine interaction (HMI) channels, such as the head [5], tongue [3] and gaze [6]. However, these channels suffer from limited resolution. Furthermore channels such as the head and gaze often cannot be controlled without sacrificing performance due to their use of the subject’s focus as the input variable. The foot which can be controlled independently of the user’s head and arms (with some constraints coming from inter-limb coordination) can provide naturally continuous

motion and force, thereby offering an intuitive mapping for control that is already commonly coordinated with the hands.

HMIs for controlling additional degrees of freedom in co-ordination with the NLs have not been studied systematically. Previous works that examine simultaneous use of the hands and foot in virtual reality (VR) include [7], who studied re-sizing, and [8] who demonstrated control of the NLs with a virtual “third hand”. In both cases, uncoupled independent three hand usage was found to be more efficient. Concurrent teleoperated SL control of two robotic arms has also been demonstrated for the tasks of lifting, grasping or holding [9], [10]. These are however preliminary studies, where control is confined to a single axis and the tasks are designed for specific applications that cannot be easily abstracted.

In this work, we assess the impact of adding a third hand task to bimanual interactions with varying coupling levels. Using the subjects’ dominant foot as an additional input channel, three different abstractions of common tasks are completed in VR requiring different levels of coordination and cognition by twenty participants. This study is, to our knowledge, the first to consider the impact of adding a third hand task to bimanual interactions with varying coupling levels, and the effect of foot-controlled interfaces on user performance when users have to coordinate concurrent motion between each limb.

II. MATERIALS AND METHODS

A. Experimental Setup

Fig. 1a depicts the study’s experimental setup. The operator was seated comfortably on a chair, holding the (Omega.7, Force Dimension) hand interfaces with both hands and placing their dominant foot in the foot interface [11]. They faced the monitor which displayed virtual task feedback.

The hand interfaces were controlled using the handles, where the vertical plane x_h and y_h (workspace $16 \times 16 \text{ cm}^2$) controlled x and y for virtual hands (VH)1 & 2 (Fig. 1b). Gravity compensation limited physical fatigue and facilitated hand control. Similarly, the foot interface (Fig. 1c) was equipped with a pedal plate that provides gravity support. The horizontal plane foot position x_f, y_f (workspace $4 \times 4 \text{ cm}^2$) * was used to control the positions of VH3 (Fig. 1b) in x_3, y_3 .

The hands and foot positions were transmitted to the PC using USB ports, synchronised with the system time and recorded at 10Hz. Feedback was displayed on a $47.3 \times 52.7 \text{ cm}^2$ screen behind the interfaces. Each $2.7 \text{ cm} \times 1.0 \text{ cm}$ VH was displayed in a $30 \times 30 \text{ cm}^2$ workspace. The three VH workspaces were designed such that any VH could reach any target.

*This smaller workspace is due to the interface’s more limited workspace.

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Fig. 1. Experimental setup. (a) complete experimental setup (b) the virtual hand display and the position controlled hand and foot interfaces. (c) experimental protocol flowchart. (d) experiment tasks.

B. Experiment Overview

Twenty healthy participants (nine females, 29.2 ± 3.1 years old, 19 right-footed) were recruited. The experiment was approved by the Institutional Review Board of Nanyang Technological University (IRB-2018-05-051) and all participants gave their informed consent before the experiment. Three tasks were designed to evaluate tri-manipulation. Within a task, trials were conducted using 2 and 3-handed operation. In 2-handed (2h) trials, only the hands were involved, while in the 3-handed (3h) case both the hands and the foot controlled the VH motion. In all trials the NLs were required to perform the same action. Thus, the 2h trial acts as the reference to study how the foot's task affects hand operation.

Fig. 1c shows the experiment flowchart. First there is a 10-minute *training phase* to familiarise with the setup and control.

Task operation then consists of a *practice*, *benchmark*, *task* and *assessment phase*. In the *practice*, the subjects were given 20 practice trials. The subjects were then randomly assigned to conduct the 20 2h trial *benchmark* or the three 20 trials per session 3h *test phase*. Finally, in the *assessment phase*, the subject filled in a questionnaire. Subjects were randomly assigned so that half started with Task 1 followed by Tasks 2 and 3 and the other half the converse.

The three tasks (Fig. 1d) were designed to reflect laparoscopic surgery where: *i*) three surgical instruments move to the target area, *ii*) two instruments move the organ to expose the tumour, while the third tool marks the cutting area, *iii*) finally, two hands cooperatively cut while the third hand suctions.

In Task 1, the VHs needed to follow three randomly moving targets that updated their position every 3 seconds. Once a target was reached, the target changed from black to green. Any VH could reach any target and in the 2h trial, the subject only needed to reach two of the three targets.

In Task 2, the hand-controlled VHs are connected by a virtual elastic band to mimic physical coupling. The subject needed to maintain this band's length and move its centre of mass (CoM) to one target, while VH3 reached another target. Visual feedback of the band length was provided: if the length was too large (30% larger than the original length), it becomes red and thins; and when it was too short (30% shorter) it changed to blue and thickened. Task 3 is similar to Task 2, however, the CoM of the elastic band should follow a path.

C. Performance Evaluation

Performance was evaluated based upon multiple measures: 1) success rate (Tasks 1 and 2), the percentage of successful trials. A trial was successful if the VHs or CoM reached the target and stayed for more than 0.2s; 2) path deviation and the travelled path number (Task 3); 3) completion time, the time for the VHs to reach the target/s; 4) jerkiness, the absolute value of the spectral arc length smoothness [12]; and 5) the VH distance travelled. Additionally, the questionnaire (Table I) evaluated the fatigue, mental load, difficulty, smoothness and time pressure of 3h operation compared to 2h operation.

III. RESULTS

The data's normality was checked using the Shapiro-Wilk method. Normally distributed data was compared using one-way repeated measure analysis of variance (ANOVA) and non-normal data with Friedman's test. If there is statistical difference among data, the Bonferroni correction was applied as a multiple comparison test for pairwise difference.

A. Task 1

Task Performance: The average success rate for the NLs in 2h trials was 93%. When VH3 was added, the NLs' success rate dropped to 85% (2h VS 3h(1), $p < 0.0005$). After two sessions, this improved to 90% with no clear difference to the 2h trials (2h VS 3h(3), $p = 0.08$). The subjects took on average 1.4s to reach the target in 2h trials and use about 13% more time to complete the 3h trials (2h VS 3h(1), $p < 0.0005$; 2h VS 3h(2), $p < 0.0005$; 2h VS 3h(3), $p = 0.001$).

TABLE I
SUBJECTIVE ASSESSMENT QUESTIONNAIRE

Statement		Score						
Compared to using 2 hands, the 3-handed operation is physically	equally tiring	0	1	2	3	4	5	extremely tiring
Compared to using 2 hands, the mental effort for 3 hands was	equivalent	0	1	2	3	4	5	very high
Compared to using 2 hands, 3-handed operation is	equally difficult	0	1	2	3	4	5	more difficult
Compared to using 2 hands, 3-handed operation is	equally smooth	0	1	2	3	4	5	less smooth
Compared to using 2 hands, the efficiency of 3-handed operation felt	equivalent	0	1	2	3	4	5	very low
In general, in 3-handed operation, which task/s is/are easy to achieve?								

Motion and coordination: There is no statistically significant difference observed in the NL's travel distance (Fig. 2a) between 2h and 3h trials ($\chi^2(3)=7.62$, $p=0.06$). Furthermore, the jerkiness (Fig. 2b) of the natural hands appears consistent across 2h and the three 3h trials ($F(3,57)=2.36$, $p=0.08$).

B. Task 2

Task performance: In 2h trials, the coupled task had a 97% success rate. After VH3 was added, the success rate of the natural hands in 3h trials decreased to 82%-86% (2h VS 3h(1), $p=0.002$; 2h VS 3h(2), $p=0.004$; 2h VS 3h(3), $p=0.008$). Associated with the reduced success rate, the completion time increased by about 25% in the 3h trials (2h VS 3h(1), $p<0.0005$; 2h VS 3h(2), $p<0.0005$; 2h VS 3h(3), $p<0.0005$).

Motion and coordination: Similar to Task 1, the addition of VH3 has not impacted the jerkiness (Fig. 2d) such that there was no clear difference between the 2h and 3h trials ($F(2.218,42.133)=12.77$, $p=0.06$). In contrast, as shown in Fig. 2c, the travelled distance of VH1 & 2 increased when VH3 was added in 3h sessions (2h VS 3h(1), $p<0.0005$; 2h VS 3h(2), $p<0.0005$; 2h VS 3h(3), $p=0.001$).

C. Task 3

Task Performance: Fig. 2e shows that the subjects initially possessed 47.7mm deviation per path without consideration of VH3. Once VH3 was added, the path deviation increased to 76.9mm per path in the first 3h trials (2h VS 3h(1), $p<0.0005$) and reduced to 63.5mm after two sessions' operation (2h VS 3h(2), $p=0.001$; 2h VS 3h(3), $p=0.007$).

Motion and coordination: The NL motion in Task 3 (Fig. 2f) does not show statistical difference on the motion jerkiness between 3h and 2h session ($F(3,57)=1.95$, $p=0.13$).

D. Foot-controlled VH Performance

In all tasks, the foot-controlled VH3 conducted the same action. For independent or coupled motion of the hands it can be observed that, in Fig. 2g, the success rate of VH3 improves from the first session to the third session of trials in Task 1 (3h(1) VS 3h(3), $p=0.02$) and Task 3 (3h(1) VS 3h(3), $p=0.01$).

E. Questionnaire responses

Fig. 3 shows the questionnaire results. The subjects felt that Task 1 was easy (median=1, interquartile range (IQR)=1), smooth (median=1, IQR=2) and without much physical (median=1, IQR=2) and mental fatigue (median=1, IQR=1) compared to using 2-hands. Moreover, the subjects felt the 3h

Fig. 2. Results. (a-f) NLs' performance: Task 1 (a) travel distance and (b) motion jerkiness. Task 2 (c) distance and (d) jerkiness. Task 3 (e) path deviation/path number and (f) jerkiness. (g) Success rate of VH3 in each task. Asterisks denote significant effects at * $p<0.05$, ** $p<0.01$, *** $p<0.001$.

operation time increased (median=2, IQR=2), which matches the experimental data. For Task 2, the subjects felt similar to Task 1 in all aspects. They felt Task 3 was more challenging than Tasks 1 and 2 ($p<0.029$) except for jerkiness (Task 2 VS Task 3, $p=0.08$). The Task 3 mental load and difficulty ratings were very high, at the highest scores of 5 for the median values, along with increased physical fatigue (median=3, IQR=1) and operation time (median=4, IQR=2). 70% of subjects chose Task 1 as easiest while 30% of subjects instead preferred Task 2. All subjects rated Task 3 as most difficult.

IV. DISCUSSION AND CONCLUSION

This study evaluated the capability of a foot-controlled third hand working together with the NLs. A VR system integrating

Fig. 3. Results of assessment questionnaire.

two hand interfaces and a foot interface was developed. The subjects' capability was then evaluated through three tasks with different coupling between the VHs. The results suggest that subjects possess the potential to use a foot-controlled interface when controlling an additional supernumerary degree of freedom in combination with their NLs. For future SL control it is however noted that the integration of the foot-interface appears to impose a limit on the speed at which bimanual tasks can be performed. Furthermore, differing levels of NL performance degradation was observed based upon the task's coupling level and path dependence.

In independent VH motion, the results suggest that a foot-controlled VH can be added with little performance loss. The addition of a foot-controlled third hand resulted in 13% slower NL operation, which may be a result of a serialisation of the tracking that occurs due to the multi-tasking taking place at the visuomotor level [13]. With minimal training there was no observed effect on the NL performance for success rate, jerkiness, travel distance and speed correlation. Subjects found the performance to be within acceptable limits and most felt the task to be easy requiring little mental effort.

In contrast, coupled NL tasks appear more sensitive to adding VH3. The success rate, completion time and travel distance were all negatively impacted, however, jerkiness was unaffected. Compared to independent motion, these tasks require NL coordination. The addition of a foot-controlled VH may therefore have a greater impact due to the continuous coordination constraint for which serialisation would more negatively impact performance. Furthermore, inter-limb coupling may have a differing impact across the two tasks. In Task 1, the actions of the hands are completely independent such that the noted negative effects of the foot's spatially incongruent motion [14] act independently on each hand. In contrast, in Task 2 the spring connection may make the negative effects of incongruency add across the congruently moving NLs, however, this would need to be further studied as it is likely a unique feature of trimanual manipulation.

In Task 3, the participants needed to dynamically follow the path accurately while coordinating their hands. When the foot was added, the participants complained about the difficulty and mental load of this task in the subjective assessment. This unsatisfactory performance may due to the varied temporal organizations of the hands and foot, which are regarded as one of the major interference to interlimb coordination [15].

In general, the subject's foot performance was found to

improve from the first to last session of trials. Given that the foot is used less for high dexterity, this result may indicate a potential such that with further sessions, the foot's operation may be less affected and even converge on the performance of the NLs. This also suggests that if sufficient and proper practice of each VH is provided, the participants may be able to successfully perform trimanual tasks without burden. However, a more systematic study of any learning is required.

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