A User-Centric Feedback Device for Powered Wheelchairs Comprising a Wearable Skin Stretch Device and a Haptic Joystick

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I. Background

In the field of human rehabilitation, user satisfaction is a vital criterion in assessing the efficacy of assistive devices. A wheelchair is a popularly researched assistive device with more than 3.5 million users in the US [1]. Through subsequent innovations, the beginnings of the wheelchair have undergone tremendous transformations to result in today's powered-wheelchair. This technological advancement has been bolstered with studies that prove the powered-wheelchair's positive impact on user's mentality and on the social cost savings per user [2].

Despite the success of the powered-wheelchair, its interface poses a learning challenge to the users during the initial stages of rehabilitation. Moreover, the inability to gain the required motor skills may render users frustrated, dissatisfied, and consequently force them to abandon the device during the premature stages of rehabilitation [2]. Several studies, aimed at resolving this issue, employed an appropriate force feedback signal via a haptic joystick [3]. However, it is believed that elderly users might struggle to fully comprehend the feedback signal owing to their weakened ability to process sensory signals. Hence a single feedback signal might prove to be ineffective [4]. Researchers have attempted to overcome the aforementioned challenge by providing feedback information through multiple sensory channels: force feedback and visual sensory cues. The underlying rationale is that information from multiple sources merge in a synergistic manner to convey a consolidated signal. The resulting multimodal system, though has proven to enhance the user's maneuverability, fell short in creating a considerable psychological impact (with Subscale scores as low as 0 for self esteem as per the Psychological Impact of Assistive Devices test) [4].

This study proposes an alternate design of feedback systems by drawing inspiration from studies demonstrating the potential of skin stretch feedback devices in improving motor task performance [5]. Moreover, it adopts a user-centric design approach with a focus on ease of operation and comfort, while exploiting the intuitive nature of skin-stretch sensory cues [6]. It is hypothesized that powered wheelchair users will benefit from a feedback device that implements skin stretch in accompaniment to force feedback.

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II. Method

For the experiment, fifteen healthy elderly adults (72.8 ± 6.6 years of age) were recruited and asked to drive a virtual powered-wheelchair through four different computer-simulated obstacle courses, while assisted by the feedback device. The feedback mechanism consisted of a haptic joystick that provided the force feedback, and a custom-designed wearable device that utilized an actuated belt to stretch the skin of the steering forearm along the direction of the arm's pronation/supination (see Fig. 1). The feedback signals were modified in accordance to the subject's deviation from a reference trajectory - the safest trajectory that was determined through previous studies with abled riders, while accounting for elderly rider's skillset [7]. To avoid any discomfort to the user and to provide the stimulus in a consistent manner, the skin-stretcher was placed on a sleeve worn over the arm. The feedback system functioned in four different modes: no-assist (NA), haptic force feedback only (H), skin-stretch only (S), and a combination of both force and skin-stretch feedback (HS). A total of 48 randomized trials were conducted by combining the four different task scenarios and four assist modes; and with each combination repeated thrice.

The following skill and safety related metrics are used to evaluate the control performance

1) *Quality of achievement* (M1) - Represents how successful the subject's trial was: passed obstacle (1 point) and reached goal (1 point)
2) *Minimum distance to obstacles* (M2) - Measures how safely the subject passed the obstacle

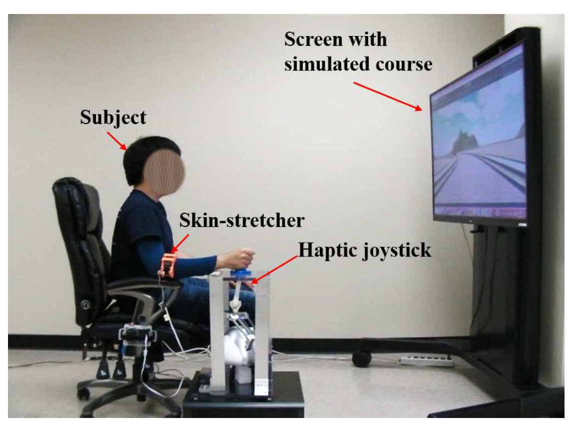

Fig. 1: Experimental setup with skin-stretcher and haptic joystick.

3) *Mean deviation from reference trajectory* (M3) - Quantifies how supportive the provided reference trajectory was
4) *Total completion time and variability* (M4) - Shows how fast and consistently the subject performed multiple trials per scenario

To further investigate the effects (main and interaction) of task and assist mode on the user's performance, a repeated measure ANOVA was performed with two factors: task and assistance mode. Significance level was set to ($p<0.05$). Significant differences among the assist modes were also studied via Bonferroni pairwise comparison with ($p<0.05$).

III. Results

Significant main effects were found for both task and assist mode in case of metrics M1, M2 and M3; however, only the result related to assist mode has been presented here. Figure 2. depicts the users' performance in terms of the four performance metrics with respect to assistance mode.

The Bonferroni pairwise comparison revealed significant difference between (1) NA and HS for metrics M1, M2, M3, and (2) S and HS assist mode in case of metric M3. Also, no significant interaction effects were recorded between the two factors. On the other hand, neither significant main effects nor interaction effects were found for metric M4. These observations consequently substantiated the hypothesis.

IV. Discussion

Statistical analysis revealed that healthy elderly subjects' control performance significantly improved when both force and skin-stretch feedback were applied. This betterment in performance can be attributed to the user-centric approach adopted in designing it and its emphasis on developing an intuitive interface. As per this approach most decisions and their validations were driven by user needs and have been enumerated as follows. (1) The system's force feedback was directly incorporated into the steering joystick. This simplification enables users to effortlessly perceive the feedback signal and appropriately alter their control input with minimal time delay. (2) The choice of skin-stretch as a feedback channel was justified through prior studies that demonstrated its intuitive nature. It was proven that skin stretch in the direction of the forearm's supination/pronation is accurately identified even by untrained users [6]. (3) The ease of operation was improved by the fact that the skin stretch feedback does not interfere with dominant sensory channels such as vision or audio - channels that should be entirely dedicated to the identification of obstacles. (4) To maximize comfort, the skin-stretcher was placed over a sleeve rather than directly on the forearm to eliminate overstretching of the skin and pulling of any body hair. (5) The nonexistence of interaction effects between task and assist mode made the required processing of the stimuli simpler and thus increased the product's user-friendliness.

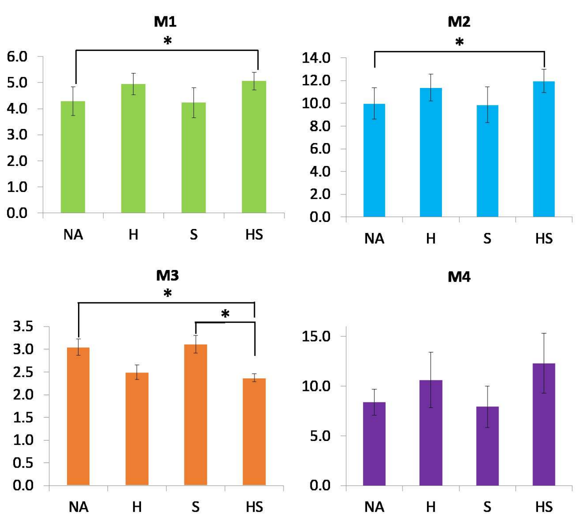

Fig. 2: Acquired user's performance in terms of four performance metrics with respect to assistance mode. '*' indicates a significant difference of $p<0.05$

To further ensure success of the product, user comfort and social costs per individual were duly considered. The skin-stretcher was designed to mimic the nature of commonly worn arm devices (such as a watch) so that it can potentially relieve any unease the users may feel, leading to high product acceptability rates. Its hands-free design also adds to the user's comfort level as it allows them to freely perform other functions. Further, the product would incur low social costs per user given that the skin-stretcher prototype was fabricated via economical means: rapid-prototyping, and standard, easily replaceable parts.

V. Conclusion

Compared to NA feedback mode, the HS condition led to significant improvements in the performance metrics; proving that the combination the skin stretch device and the haptic joystick encourages synergistic effects to improve users' hand motor control. It is also expected that owing to the customer need-driven decisions made throughout the product development phase, the proposed feedback device is more intuitive to operate and could potentially improve user satisfaction.

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