# Tradeoffs in kinesthetic feedback: An evaluation in body-powered grasp assistance

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## I. INTRODUCTION

Loss of function in a hand negatively impacts a person's ability to perform activities of daily living (ADLs), and fully replicating the dexterous capabilities of the human hand remains a challenge for clinicians and scientists alike [1]. Recent works have sought to evaluate the potential for passive systems to act as more functional interfaces for wearable devices [2], [3]. The cable actuation of body-powered prostheses, for example, allows for more robust control and feedback when compared to alternative modalities such as myoelectric devices [4]. By coupling the force and motion of the contralateral shoulder to that of the end-effector, users are able to relate kinesthetic cues and motor inputs at the shoulder to the state of a grasp. The lightweight and robust nature of passive cable-driven systems have also made them popular in the design of grasp assistance devices for individuals with paresis or paralysis [3].

However, body-powered devices can require high muscle forces to operate which present risk exposures to fatigue and discomfort for users, especially during extended periods of operation [6]. In this work, we aim to understand the relationship between the kinesthetic feedback present in body-powered devices and user exertion, as well as the associated design considerations for assistive technologies. We expand on previous work by considering displayed force feedback along a continuous scale to gain insight into trends in grasp performance [2]. Furthermore, we evaluate grasp performance through applied forces during an experimental grasping task rather than decision-oriented tasks such as haptic discrimination.

## II. METHODS

In order to systematically vary the magnitude of force feedback provided to participants during a grasping experiment, we developed a test bed comprised of three main components: a shoulder harness actuated by a custom haptic interface, a simulated grasping environment with a graphical user interface (GUI), and a height controller.

### A. Test Bed Design

The participant wears a figure-of-nine prosthetic harness on their left shoulder with an attached Bowden cable running to the haptic interface, which transmits haptic information to and from the user during device operation. The haptic interface relates cable position and force to that of a motor shaft with an encoder. Cable excursion due to shoulder adduction and abduction, measured by the encoder, controls the aperture of the simulated gripper and its applied grasp force. This applied force is scaled by a force feedback factor $K_f$ by the equation $F_{feedback} = K_f F_{grasp}$, to change the setpoint for a motor current controller to output force to the user. The participant raises and lowers the virtual gripper using a separate height controller with their right hand.

### B. Study Procedure

Each trial consists of an experimental grasping task modeled after similar studies with normative human hands [7]. Participants first grasp and lift the virtual test object in the simulated environment displayed in the GUI using the shoulder harness and height controller up to a height of at least 15 cm, noted by a dashed line. Object parameters are set to require at least 7 N of grasp force to lift. They then attempt to hold the object above this line for at least 5 seconds. They complete one trial by releasing the test object and returning the gripper to the ground level.

Each participant completes ten grasping trials at each of five different force feedback factors: 0 (no feedback), 0.33 (light feedback), 0.67 (moderate feedback), 1 (equal feedback), 1.33 (augmented feedback). A Fisher-Yates shuffle pseudorandomizes the order of feedback factors for each participant, which is not revealed at any point during the experimental session.

Data represent a total of 9 non-amputee participants with normative upper limb function. All experimental procedures are approved by the University of California, Berkeley Institutional Review Board protocol #2019-05-12178.

### C. Data Analysis

Force and height data are recorded throughout each trial at a rate of 50 Hz. We then calculate a range of metrics to characterize trial performance, namely the mean grasp force and mean absolute deviation (MAD) of force while holding the test object, peak grasp force, and number of drops.

Due to observed within-subject correlation and the continuous nature of the data, linear mixed models (LMM) are used to separately relate the mean grasp force, peak grasp force, and grasp force MAD to the predictor variables of force

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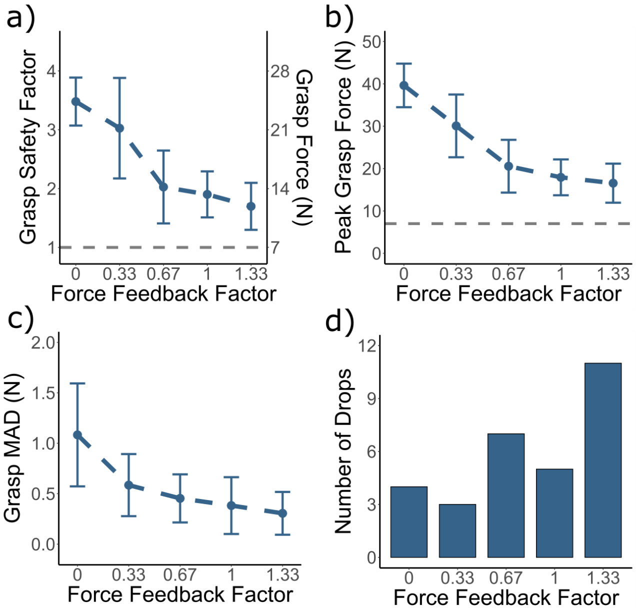

Fig. 1. Summary of data on grasp performance metrics: a) Overall mean grasp force in newtons and safety factor across all participants at each feedback factor. b) Overall mean peak grasp force in Newtons across all participants at each feedback factor. c) Overall mean Mean Absolute Deviation (MAD) of grasp hold force across all participants at each feedback factor. d) Number of drops out of 90 total trials between all participants at each feedback factor. Error bars denote standard deviation of subject means at each feedback factor.

feedback factor ($K_f$, fixed effect), feedback factor order ($FO$, covariate), and trial order ($T$, covariate). Participant ID is added as a random (slope and intercept) effect for all mixed models.

Generalized linear models (GLM) capture the non-continuous outcome of drop chance using a binomial logistic regression model. Predictor variable structure remains the same as described as above. No significant within-subject correlation is observed, so no random effect for participant ID is included for model parsimony.

## III. RESULTS

Participants apply lower grasp forces to and maintain steadier grasps of the test object with increasing force feedback factor, shown in Fig. 1(a-c). The mean grasp safety factor across participants, defined as the ratio between the mean holding grasp force and the minimum grasp force required for lift-off, reduces by a factor of two between the minimum and maximum force feedback factors presented in this experiment. Similar trends appear in the peak force and force MAD data, with decreases from 39.6 N to 16.6 N and from 1.08 N to 0.31 N, respectively. After accounting for covariates and random effects, the linear mixed models show a significant effect of force feedback factor on mean grasp force ($b = -0.318$, $p = 0.004$), peak grasp force ($b = -0.597$, $p < 0.001$), and grasp force MAD ($b = -0.756$, $p < 0.001$).

Participants also drop the test object more often at higher force feedback factors, shown in Fig. 1(d). A drop rate of 4.44% (4 drops out of 90 trials) occurs with no force feedback ($K_f = 0$), while a drop rate of 12.2% (11 drops out of 90 trials) occurs at the highest factor ($K_f = 1.33$). Results from the binomial regression model also indicate a significant effect of force feedback factor ($b = 0.887$, $p = 0.036$).

## IV. DISCUSSION AND CONCLUSION

Consideration of feedback along a continuous spectrum reveals a non-linear and monotonically decreasing relationship between our grasp force metrics and force feedback factor, with diminishing changes at high factors. This suggests the potential for substantial improvement in grasp force control using only light or moderate displayed forces. This would be of particular importance for the consideration of force feedback in the design of many haptic and wearable technologies where minimizing the weight and size of haptic actuators or passive transmissions is essential for usability.

Direct generalizability of the findings to real-world environments is somewhat reduced by the simulated nature of the experimental grasps. We limited user feedback to only vision and shoulder harness forces to better isolate the role of force feedback factor, and future work will explore how additional physical interactions, such as weight perception, influence body-powered interface function.

This work illustrates several design considerations in body-powered device interfaces. The provided additional sensory knowledge of a grasp state allows individuals to better apply predictable and stable internal grasp forces while interacting with their environment. Yet, the increased loads applied to their bodies also render them more prone to drops as well as fatigue-related risk exposures. Balancing these observed effects could lead to more functional and widely adopted technological interventions for grasp assistance.

## REFERENCES

[1] D. Datta, K. Selvarajah, and N. Davey, “Functional outcome of patients with proximal upper limb deficiency–acquired and congenital,” *Clinical Rehabilitation*, vol. 18, no. 2, pp. 172–177, Mar. 2004, publisher: SAGE Publications Ltd STM.

[2] J. D. Brown, T. S. Kunz, D. Gardner, M. K. Shelley, A. J. Davis, and R. B. Gillespie, “An Empirical Evaluation of Force Feedback in Body-Powered Prostheses,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 25, no. 3, pp. 215–226, Mar. 2017.

[3] L. Gerez, J. Chen, and M. Liarokapis, “On the Development of Adaptive, Tendon-Driven, Wearable Exo-Gloves for Grasping Capabilities Enhancement,” *IEEE Robotics and Automation Letters*, vol. 4, no. 2, pp. 422–429, Apr. 2019, conference Name: IEEE Robotics and Automation Letters.

[4] S. L. Carey, D. J. Lura, M. J. Highsmith, CP, and FAAOP, “Differences in myoelectric and body-powered upper-limb prostheses: Systematic literature review,” *Journal of Rehabilitation Research and Development*, vol. 52, no. 3, pp. 247–262, 2015.

[5] M. Abbott, J. Fajardo, H. W. Lim, and H. Stuart, “Kinesthetic feedback improves grasp performance in cable-driven prostheses,” p. 7, In press 2021.

[6] M. Hichert, A. N. Vardy, and D. Plettenburg, “Fatigue-free operation of most body-powered prostheses not feasible for majority of users with trans-radial deficiency,” *Prosthetics and Orthotics International*, vol. 42, no. 1, pp. 84–92, Feb. 2018.

[7] R. Johansson and G. Westling, “Roles of glabrous skin receptors and sensorimotor memory in automatic control of precision grip when lifting rougher or more slippery objects,” *Experimental Brain Research*, vol. 56, no. 3, Oct. 1984.