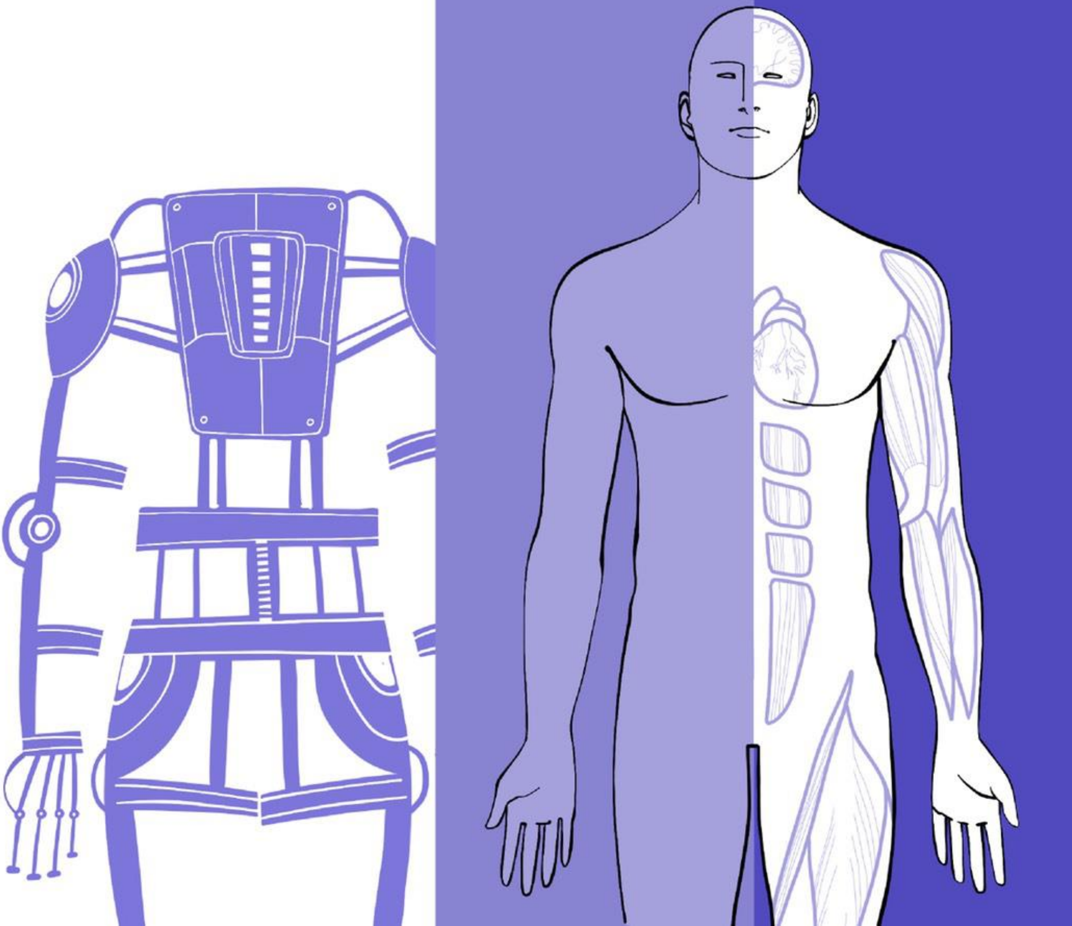
Assistive Technology Considering Human Characteristics

Design guideline
for power assistance

Presented by: *The Research Team of Human Adaptation for Power Assistance*



Contents

Part 1

Intro

Part 2

Design issues

Part 3

Human responses during cooperation

Part 4

Preface

In the recent years, there has been considerable progress in the development and application of assistive technologies, i.e. devices that provide movement assistance, for human power augmentation. These assistive devices are often in the form of powered exoskeletons, which are wearable frames that are driven by a system of actuators. When worn, these promise to provide marked improvements in the user's strength and performance, enabling users to overcome a disability or enhance their biological capacities. However, to produce assisted movements that are both smooth and precise, we need to have a grasp on the kinds of latent human capabilities that can be leveraged to optimize the control of these powered assistive devices.

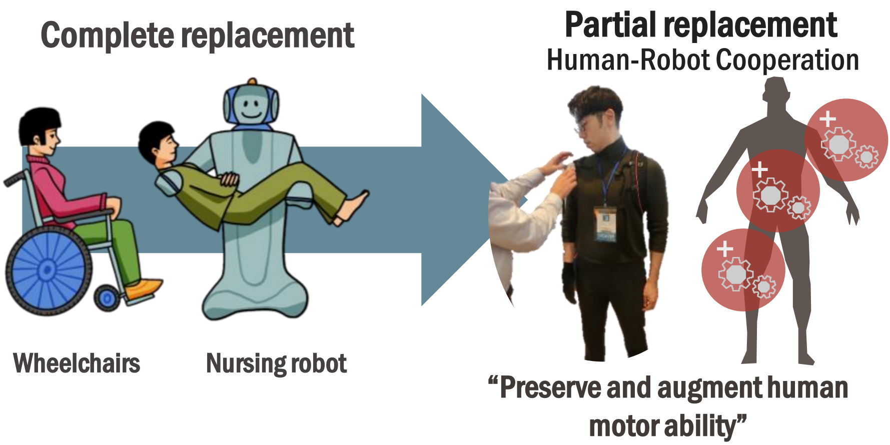
It is from this perspective that we have prepared this booklet, which aims to support the design and development of devices that provide movement assistance. This booklet was based on our research that aimed to shed light on the physiological adaptations of humans to external forces from assistive devices[1)]. We hope that the guidelines outlined in this booklet can help developers and designers gain a new perspective on the inherent human capabilities and lead to improvements in the next generation of powered assistive devices.

1) "Understanding and application of human adaptation to power assistive technology," Grant-in-Aid for Scientific Research of Japan Society for the Promotion of Science.

Defining movement assistance

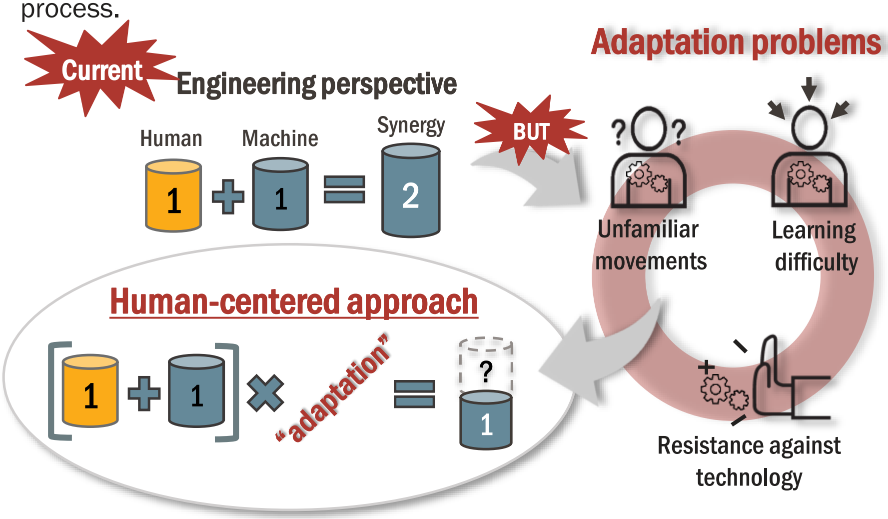
The main objective of movement assistance is to maintain or enhance human motor capability. Using these technologies, we can reduce the physical burden on workers in occupations that require harsh physical labour, such as nursing, farming or warehouse work, and also improve the quality of life of older adults whose physical capabilities have declined due to age-related disabilities.

Unlike other assistance solutions where the device completely replaces the existing human function (e.g. the user no longer uses their legs), such as wheelchairs and nursing robots, devices that provide movement assistance, such as exoskeletons, instead augments the existing human function. The latter does so by providing assistive forces that reduce the physical burden associated with performing a task. However, because the execution of tasks requires the human and machine components to work together, effective human-machine cooperation is essential for optimal movement assistance.



Human adaptations to assistance

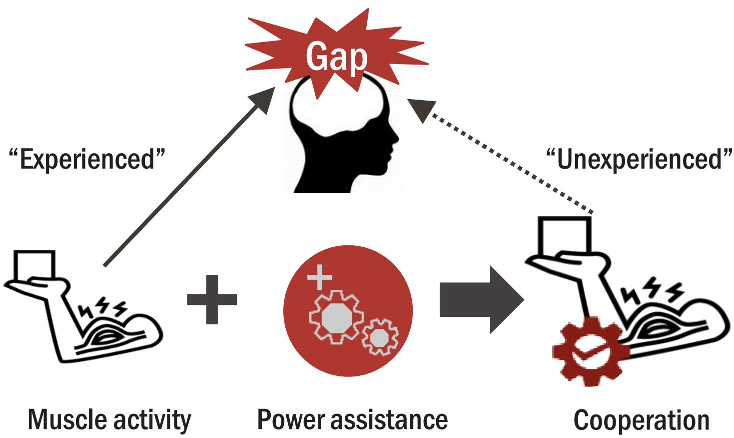
Assistive technology does not only include movement assistance but also extend to other human functions. When considering the actual usage of these technologies, the problem of human adaptation arises. It has been pointed out that current assistive technologies have been developed with a technology-oriented perspective. From that point of view, integrating the two components of humans and machines will directly lead to a synergistic performance. However, from the human-oriented perspective, such a synergistic performance is difficult to achieve because the assistance from the machine requires shared control for humans, something that has hardly been experienced before. Specifically, if the cooperation does not provide synergistic performance continuously during its early stages, human users may feel resistance toward the technology. Therefore, before extensive use of the assistive technology, it is important to identify and clarify various human adaptation problems that might appear during the actual cooperation process.



How machines assist vs. how humans feel

Human movements with power assistance involve an extremely complex process of motor control and learning. Effective movement cooperation can only be achieved when the user is able to adjust the magnitude of their muscle-tendon tension and the corresponding joint movement with the magnitude of assistance (e.g. power, velocity, displacement, etc.).

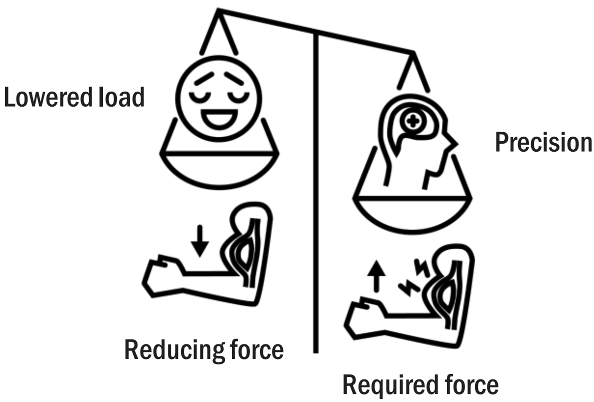
However, even if an external force is provided by powered assistive devices, questions remain on whether humans can actually perceive the reduction of physical load during the cooperation. For instance, if an assistive force is applied to the arm when lifting a weight, humans can be confused by various sensations (position sense, kinesthetic sense, resistance, etc.) because of the differences in the motor experiences, with and without assistance.



Dilemma: lowering load vs. task precision

When power assistance is provided, the user has two objectives to meet. One is to take the externally applied assistive force and reduce the muscle force (tension) to "lower the physical load on the body." The other is “task precision” in order to control detailed joint displacement or force exertion, which requires a certain magnitude of tension of the multiple muscles. Cooperation with assistance makes it difficult to meet both objectives at the same time. For example, if the precise performance of cooperation is prioritized, then the effect of lowering the physical load might be diminished. Therefore, the effects of power assistance and human augmentation need to be evaluated from the point of view of this physiological dilemma.

“Completion of human augmentation”



Factors affecting human-machine cooperation

Human movement mechanisms in daily life and in industrial settings are complicated and so are the corresponding specifications of power assistance devices. Therefore, questions and issues may arise based on the human and mechanical factors listed below. For example, what is the human motor capability for the varying assistive forces and speeds? How will users adapt to multiple-joint assistance? How are the patterns of adaptation affected by the different body parts (e.g. upper and lower limb; dominant and non-dominant limb)? These kinds of questions will continue to arise as the technology becomes more advanced.

Mechanical factors

- ✓ Targeted movement
- ✓ Control (Actuator)
- ✓ Force, velocity
- ✓ Magnitude, timing
- ✓ Precision
- ✓ Safety
- ✓ Degrees of motion freedom
- ✓ Feedback provision
- ✓ Weight (batteries)

Human factors

- ✓ Age/Sex
- ✓ Mobility
- ✓ Perceptibility
- ✓ Learnability
- ✓ Experience level
- ✓ Trust level
- ✓ Usage time
- ✓ Working condition
- ✓ Limb dominance

■ Considering human factors on design

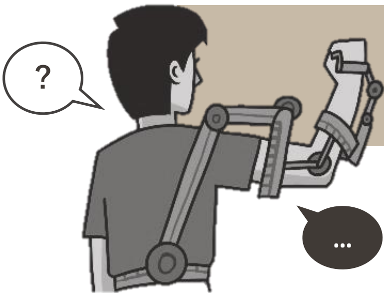
It is not easy for humans to use assistive technology to enhance their motor abilities. Specifically, humans have to face the new problem of adapting their actions in order to cooperate with the technology-provided assistance. Firstly, perceptual gaps can arise between manual movements, which are commonly performed, and assisted movements. Secondly, there is a physiological dilemma between lowering the physical load and enhancing task precision. Therefore, in the process of developing and designing assistive devices, it is desirable to understand the effects of various human factors and characteristics that may arise during the cooperation process.

＜Our research approach＞

⚠ 1. Problems during cooperation

- How to adapt?
- How to perceive?
- Physiological dilemma?

What should be considered?



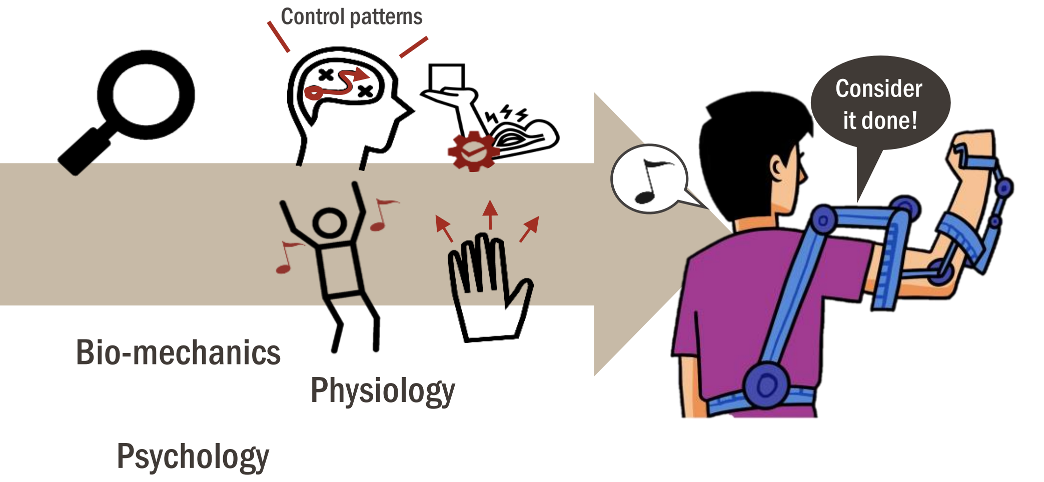
Our research team investigates human characteristics, such as biomechanical, physiological, and psychological responses, based on the simulated use of assistive technology. We are currently performing research to provide optimal power assistance and mechanical functions that reflect human factors and to enhance learnability and adaptability. We hope this could be a guideline not only for the improvement of human-robot cooperation but also for the desirable coexistence of innovative technologies and human beings.

2. Proactive study

"Explore human characteristics"

3. Design guidelines

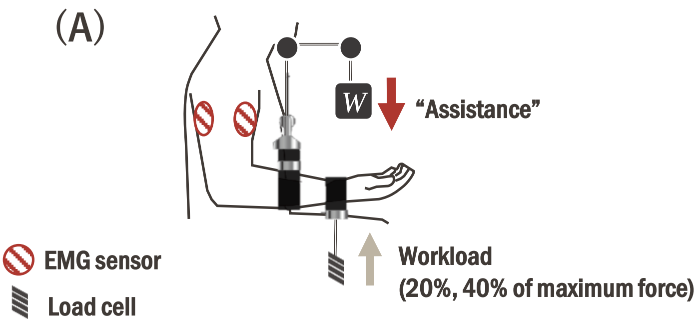
"Optimal cooperation and extension of human motor abilities"



"How well can assistance reduce muscle load?"

In order to understand muscle activation patterns when an assistive force is provided, we conducted an experiment on the elbow flexor. Twenty-five participants, who were in their twenties, were asked to flex their elbow at 90 degrees, as shown in Figure A[2]. Lower and higher physical loads (20% and 40% of each participant's maximum elbow flexor force) were applied, while an assistive force was provided by weights through a pulley system. Surface-electromyography (EMG) was recorded to estimate muscle activity, and a load cell was used to measure the changes in force applied by the elbow flexor.

The results showed that muscle activity generally decreased with an increase in the assistive force (weight). However, the decrease in muscle activity was not proportional to the level of assistance. As the red lines in Figure B indicate, the increased assistive force failed to sufficiently reduce muscle activity, with the difference being more more noticeable when the physical load was lower.



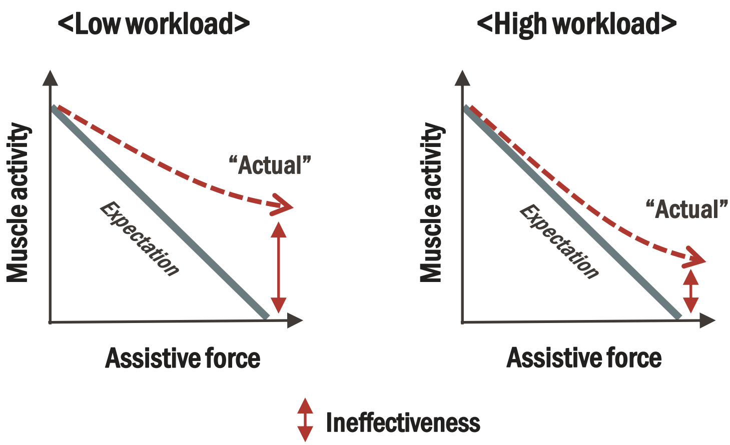
2) Loh, P. Y., Hayashi, K., Nasir, N., & Muraki, S. (2020). Changes in Muscle Activity in Response to Assistive Force during Isometric Elbow Flexion. *Journal of Motor Behavior*.

These results demonstrate that although assistive force might be effective for tasks with higher physical loads, synergistic cooperation and shared control might not occur even if the assistive force is increased. Furthermore, the results of assistance at lower workloads indicated that, rather than utilizing assistive force, humans might prefer manual force control and postural stabilization during cooperation.

Design guideline

- Power assistance is effective when the workload is higher
- Effectiveness of assistance decreases if assistance level increases
- If assistive force is not sufficiently provided, humans tend to prioritize manual control during cooperation

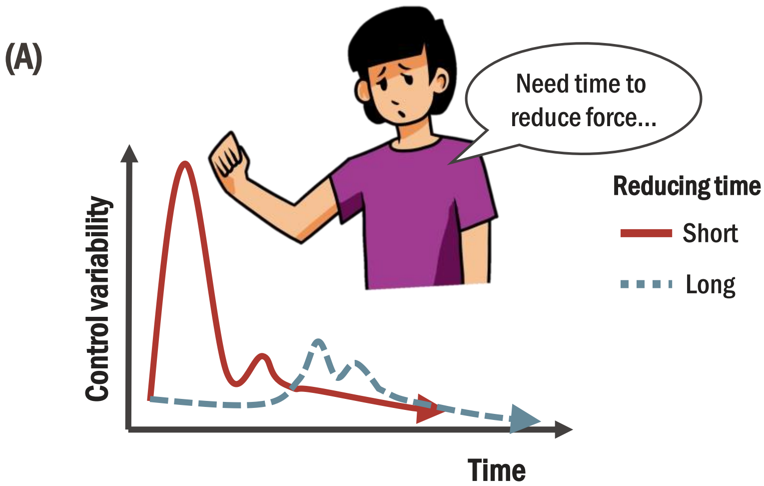
(B)



Before exploring human-robot cooperation,

“Human ability to reduce force and muscle load?”

If the motor responses of manual force reduction during static force control of elbow flexor are explored, the characteristics and control patterns of force reduction by assistive force can be compared and estimated. Twelve participants in their twenties were asked to sit on a chair with their elbow at 90 degrees. Using visual guidance provided on a computer screen in front of them, they were then instructed to reduce their muscle force without any assistance[3). The duration and magnitude of force reduction were controlled by varying the forms of visual guidance.



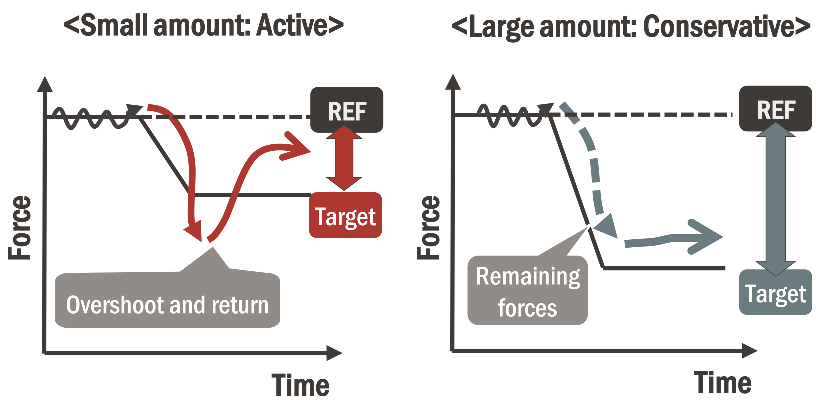
3) Choi, J., Yeoh, W. L., Loh, P. Y., & Muraki, S. (2019). Force and electromyography responses during isometric force release of different rates and step-down magnitudes. *Human Movement Science.*

The results indicated that force variability will decrease if the duration for force reduction is extended (Figure A). However, the extended duration produced increased the antagonistic muscle activity (triceps brachii muscle). On the other hand, this study showed that the force control pattern varied based on the conditions of force reduction: while a reduction in the magnitude of weak force led to increased overshoots (Active), a reduction in the magnitude of a strong force led to a more gradual move toward the target (Conservative) (Figure B).

Design guideline:

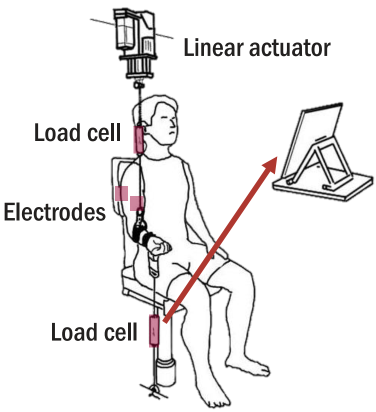
- **Force reduction time should be presented sufficiently for it to lower control variability**
- **Control patterns that vary based on the magnitude of force reduction can be avoided or utilized in providing assistance**

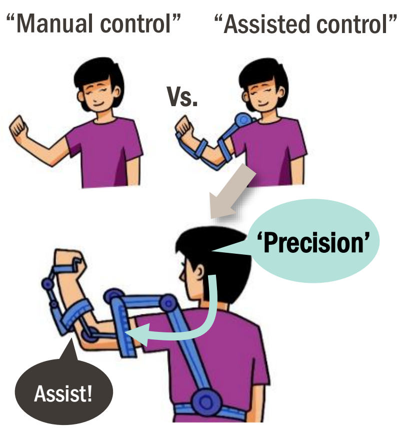
(B)



“Muscle force control characteristics during cooperation?”

The reduction of muscle activity by assistive force might be different from that by manual control without assistance. Thirteen individuals participated in this experiment, and a linear actuator was used to apply assistive force during elbow flexion of each participant[4]. Participants were asked to reduce their static muscle force by either following a visual guide shown on the screen or by applying an assistive force. We analyzed components of each participant's muscle activity patterns and found that components which are related to precise motor output increased when assistive force is provided. This suggests that human motor control systems adopt distinct physiological strategies during cooperation with mechanical assistance.





4) Choi, J., Yeoh, W. L., Matsuura, S., Loh, P. Y., & Muraki, S. (2020). Effects of mechanical assistance on muscle activity and motor performance during isometric elbow flexion. *Journal of Electromyography and Kinesiology.*

“Effects of assistance on multi-joint force control?”

The dominant arm is generally preferred when performing movements related to daily living and manual work. In another study, we focused on the hypothesis that hand-dominance might affect the performance and physiological responses during cooperation with assistance. Thirteen individuals participated in this experiment, which examined the muscle activity of each arm when assistive forces were provided[5)]. The results indicated that the effectiveness of muscle activity reduction diminished in the non-dominant arm, revealing that the cooperation can be affected by the individual's movement familiarity and skillfulness.

On the other hand, the performance of the assisted arm may have been affected by the unassisted arm. In a follow-up experiment, we recruited 11 participants and compared the effects of physical load on the unassisted arm (manual work) when assistance was provided to the other arm[6)]. Although the assistance provided improved stability on the assisted side, the effectiveness of muscle activity reduction diminished on the unassisted side.

Design guideline

- Provide assistance considering the level of movement familiarity

Design guideline

- Manual work of unassisted joint movement might affect performance

5) Wang, Y., Choi, J., Loh, P. Y., & Muraki, S. (2019). A comparison of motor control characteristics of the dominant and non-dominant arms in response to assistive force during unilateral task. *Isokinetics and Exercise Science.*

(Continued)

“Effects of assistance on multi-joint force control?”

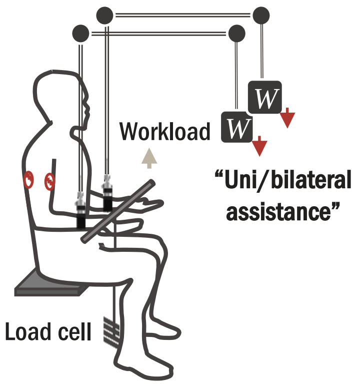
We also investigated the effects of assistance on the performance of both-arm (bilateral) movements. Fourteen participants in their twenties were recruited and were asked to lift a ground-connected bar, while maintaining an assigned level of tension (Figure A). Assistive forces were then provided on either arm or both arms through a pulley system.

The results showed that force variability and subjective workload decreased when assistive forces were provided on both sides (Figure B).

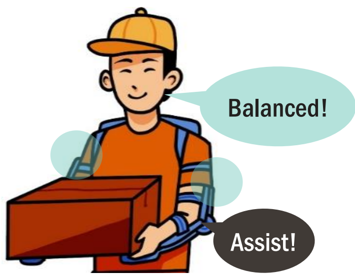
Design guideline

- **Balanced assistance should be provided if both-arm (bilateral) movements need to be supported**

(A)



(B)



6) Choi, J., Yeoh, W. L., Loh, P. Y., & Muraki, S. (2020). Motor performance patterns between unilateral mechanical assistance and bilateral muscle contraction. *International Journal of Industrial Ergonomics.*

Compared with young adults,

“How do older users perceive cooperation?”

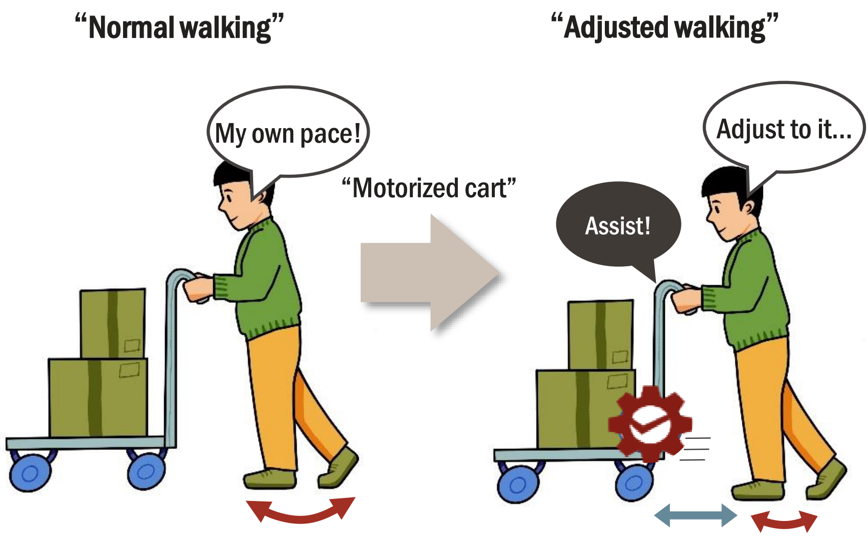
Older adults, who usually have decreased physical capabilities, are expected to be the user group to benefit the most from physical assistive devices. It is important to understand how they perceive the externally provided assistive force compared to younger adults. We recruited 12 older adults and 10 younger adults and conducted the experiment shown in p. 9. The assistance did generally reduce the muscle activity of both groups. However, the older adults could not accurately perceive the reduced level of muscle activity due to the assistance provided. This implies that even if older adults have the ability to reduce muscle load when assistance is provided, their attention tends to focus on adjusting to the assistive force itself, rather than perceiving the level of assistive force.

Design guideline

- **Sufficient explanation regarding the benefits of assistance should be provided to older users**
- **Sufficient time to adapt to cooperation should be provided for older users**

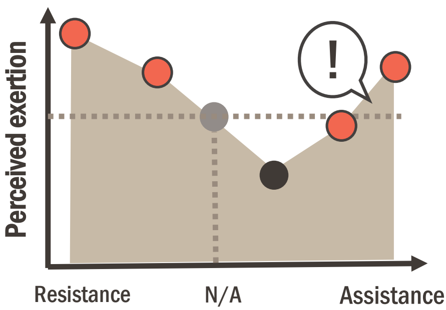
“How do motorized carts affect walking motion?”

Today, there are motorized carts that use electric motors to provide assistive force. However, how users cooperate with the assistance force has yet to be investigated. A 3D motion capture system was used to evaluate human motion characteristics when walking with a motorized cart. In one study, the joint movements and gait parameters were analyzed in 13 participants in their twenties who were tasked to walk 10 m with the motorized cart. When walking with a motorized cart, the user’s walking pattern became more passive with shorter step length, relative to walking with a non-motorized cart. In other words, users adapted their gait to the motion of the motorized cart.



“How do motorized walkers affect perceived exertion and walking motion?”

Our research team has also performed research on Smart Walkers, which can provide various smart features to better assist a users' walking. To be used as a testbed, we developed an experimental Smart Walker whose assistive force and speed could be controlled. Eighteen participants in their twenties were asked to walk 10 m with the walker while different magnitudes of assistive (and resistive) forces were provided[7]. The results showed that in moderate assistive force level, perceived exertion decreased to its lowest point, while gait parameters remained constant. Further intensifying the force, however, increased perceived exertion and led to the users choosing to walk at higher speeds. Hence, the use of assistive forces when developing Smart Walkers needs to be carefully considered to provide safe and effective support to its users.



Design guideline

- Assistive force and speed of motorized walker should be set based on the user’s mobility level

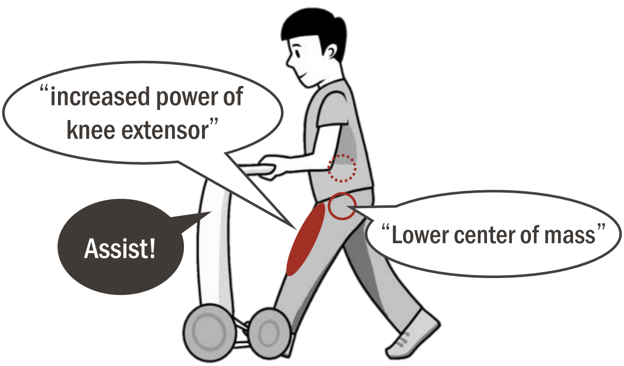
7) Yeoh, W. L., Choi, J., Loh, P. Y., Saito, S., & Muraki, S. (2020). The effect of horizontal forces from a Smart Walker on gait and perceived exertion. *Assistive Technology.*

(Continued)

“How do motorized walkers affect perceived exertion and walking motion?”

Smart Walkers are generally used to support older adults or people with walking impairments, but they may lead to a different walking pattern, when compared to normal walkers. Nineteen participants in their twenties walked 10 m with the experimental Smart Walker, with the walking motion being recorded using a 3D motion capture system.

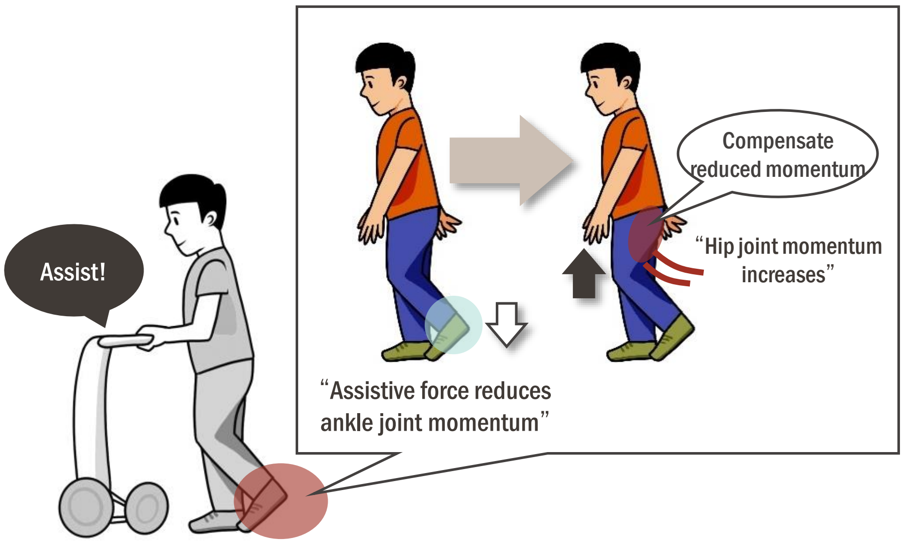
The results showed that the higher the magnitude of the assistive force provided, the lower the center of mass of the user and the higher the power of the knee extensor during heel contact. Human walking involves both propulsion (during push-off) and braking (during heel contact). Although the assistive force reduces the work for propulsion, it also creates the problem of increased work required for braking.



In addition, force platforms embedded in the walkway were used to calculate the lower limb joint powers of the participants. When assistance was provided, the work was performed at the ankle joint (plantarflexion) during push-off. However, this reduced the momentum required for the subsequent foot swing motion. Hence, the work done at the hip joint (extension) increased. In other words, there are both positive and negative aspects to the assistance provided by the Smart Walker.

Design guideline

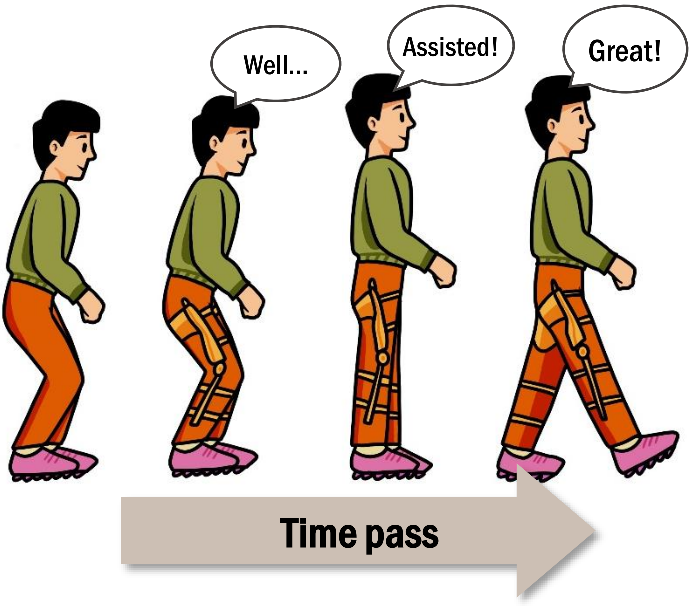
- **Humans adjust walking patterns when assistive force is provided**
- **The effect of walking assistance is limited to a specific joint movement**
- **Reduced physical load on one joint movement causes increased load on the other joint movement**



“Effects of walking with an assistive suit?”

Assistive technology for augmenting human mobility might affect the physical, physiological, and psychological responses of its users. For 30 participants in their twenties, we analyzed the motion when walking with an assistive suit. We also performed subjective evaluations on various aspects of usability and user experience.

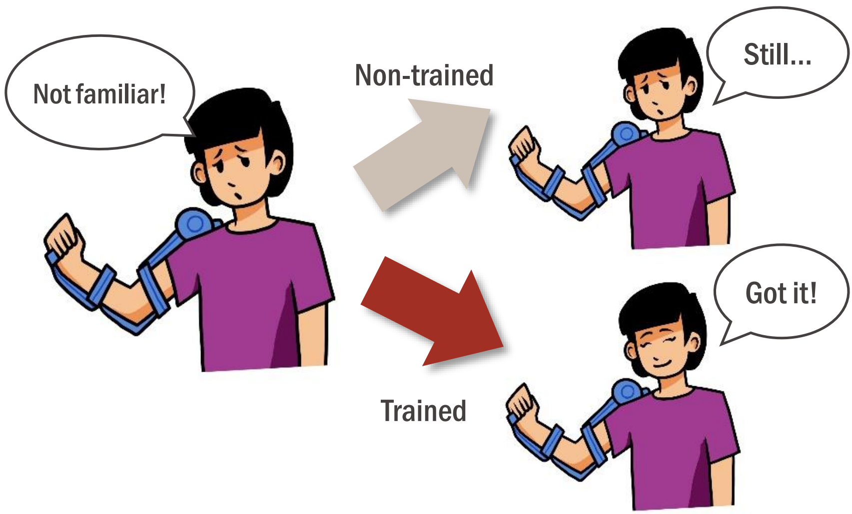
According to the results, users perceived that their physical load required for walking was reduced over time. However, they were not able to identify the level of assistance provided.



“How does training affect cooperation?”

We conducted an experiment to investigate if training sessions could improve the users’ performance when cooperating with an assistive device. We recruited 19 participants in their twenties, who were then asked to perform the experimental task shown in p. 9 for 4 days. The participants were divided into two groups: nine joined training sessions of shared control with assistive force (50% of each participant's maximum force) in days 2 and 3, while the others were not trained.

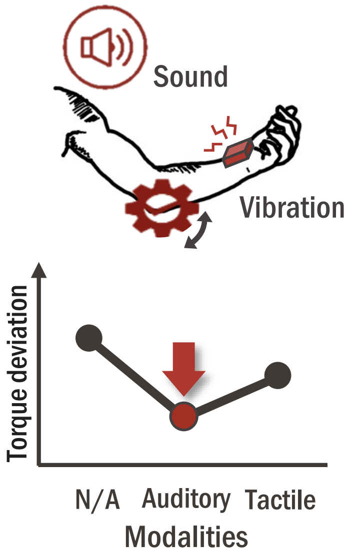
The results showed that the trained users had lower force variability during assisted force control than non-trained users. This suggests that humans can adapt to assistive force and obtain the appropriate skills for cooperation via training sessions.



Others

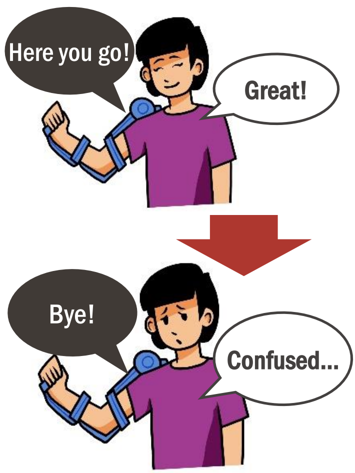
<Effects of sensory feedback>

Multi-modal sensory feedback can be provided to improve cooperative performance. Twelve participants in their twenties were asked to generate a constant level of torque during elbow flexion with controlled angular velocity. When the generated torque was higher or lower than the allowed interval, sensory feedback was provided by either sound (auditory) or vibration (tactile) on the forearm. The results demonstrated that auditory feedback decreased torque deviation the most, followed by tactile feedback.



<Effects of assistance lost>

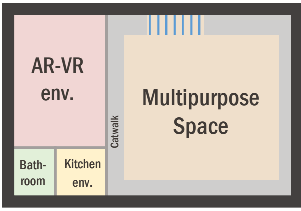
When cooperation with assistance is initiated and lost, humans experience task switching between manual and shared control of cooperation. This transition might confuse the human motor control. Our experimental data indicated that the variability particularly increased when assistance was lost, i.e. transition from shared control to manual control.

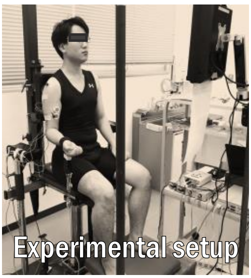


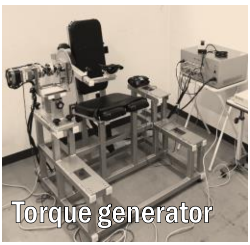
Research Facility and equipment

Living Space Experiment House

- **3D motion capture system**
  - 11 high-speed infrared cameras
  - 10 m walkway
  - Experiments conducted on various human motion
- **3D printer**
- **AR ・ VR environment**
- **Wireless data acquisition**
  - EMG sensor ・ accelerometer







Gym annex laboratory

- **Pulley system for experiments**
- **Linear actuator**
- **Torque generator**
- **Wired data acquisition**
  - EMG sensor
  - Accelerometer
  - Load cell
  - Dynamometer
  - etc.

Publication (Current in Nov. 2020)

International Journals

- J. Choi, W.L. Yeoh, P.Y. Loh, S. Muraki. Motor performance patterns between unilateral mechanical assistance and bilateral muscle contraction. International Journal of Industrial Ergonomics. Vol. 80, Article No. 103056, 2020
- W.L. Yeoh, P.Y. Loh, S. Saito, S. Muraki. Interaction between a motorized walker and its user: effects of force level on within-stride speed and direction fluctuations. Journal of Ambient Intelligence and Humanized Computing. 2020
- W.L. Yeoh, J. Choi, P.Y. Loh, S. Saito, S. Muraki. The effect of horizontal forces from a Smart Walker on gait and perceived exertion. Assistive Technology. 2020
- J. Choi, W.L. Yeoh, S. Matsuura, P.Y. Loh, S. Muraki. Effects of mechanical assistance on muscle activation and motor performance during isometric elbow flexion. Journal of Electromyography and Kinesiology. Vol. 50, Article No. 102380, 2020
- P.Y. Loh, K. Hayashi, N. Nasir, S. Muraki. Changes in muscle activity in response to assistive force during isometric elbow flexion. Journal of Motor Behavior. 52(5), 634-642, 2019
- J. Choi, W.L. Yeoh, P.Y. Loh, S. Muraki. Force and electromyography responses during isometric force release of different rates and step-down magnitudes. Human Movement Science. Vol. 67, Article No. 102516, 2019
- Y. Wang, J. Choi, P.Y. Loh, S. Muraki. A comparison of motor control characteristics of the dominant and non-dominant arms in response to assistive force during unilateral task. Isokinetics and Exercise Science. 2019
- S. Muraki. Human-centered design for advanced technology. Advances in Social Science, Education and Humanities Research. Vol. 207, 2018

Conference and Exhibition

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