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Characteristics of Muscle Activity and Joint Dynamics During Weight Lifting by Isotonic Elbow Flexion With Assistive Force

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ABSTRACT

[Objectives] This study focused on submaximal weightlifting (stopping at a targeted height) by elbow flexion and investigated the differences in muscle activity and joint dynamics under assisted and unassisted conditions. [Methods] Eight young adults lifted weights (equivalent to 15% of the biceps maximal voluntary contraction [MVC]) by isotonic elbow flexion with and without assistive force using our originally developed impedance-controlled assistive devices. The participants lifted weights to achieve a reference target on the screen (the angular position of the wrist) and terminated the movement at the specified target stopping position. During the task, we measured the dynamics of the elbow joint movement, as well as the co-contraction index of the biceps brachii (BB) and triceps brachii (TB) using electromyography (EMG). [Results and Discussion] The rectified EMG waveforms for the BB and TB exhibited a bimodal and unimodal waveform under the assisted and unassisted conditions, respectively. Under the assisted condition, the elbow joint angle tended to overshoot the target stopping position, suggesting that additional effort was required to accurately terminate the elbow flexion. [Conclusion] It was suggested that although humans could use an assistive force to reduce the muscle load, they have unique motor control to maintain joint movement accuracy.

Keywords: Exoskeleton, Motor control, Electromyography, Cooperation, Co-contraction, Overshoot

INTRODUCTION

Recently developed applications for human power augmentation have attempted to directly manipulate human joint movements using advanced sensing and motor control technologies (De Looze et al., 2016; Winter et al., 2021; Eden et al., 2022). The primary aim of such applications is to reduce the physical workload of manual tasks, such as caring for a bedridden person or repeatedly carrying a heavy load. To date, many previous studies have evaluated the effectiveness of their applications by measuring the working muscle activity using electromyography (EMG), or by evaluating its metabolism using the oxygen uptake and heart rate (Martini et al., 2019; Qu et al., 2021; Erezuma et al., 2022; Garcia et al., 2023).

However, to enhance the effectiveness of such applications, it is important to optimize co-cooperation between the users and the applications themselves (Bequette et al., 2020; Stirling et al., 2020; Yeoh et al., 2023). The assistive forces provided by such applications are a disturbance for dynamic joint movements. A user must first perceive the assistive force via various proprioceptor receptors and then instantly modify their motor control to effectively use that force as their own external force. To reduce muscle activity, the users must try to release the primary working muscle force. However, the release of force is known to be more difficult than the increase in force in terms of performance stability (Naik et al., 2011); moreover, Choi et al. (2019) revealed that the control strategies for the release of force can be either conservative or risky depending on the targeted step-down magnitude. Furthermore, as power assistance causes external perturbations of the joint, specific motor unit activity could be required to dampen the perturbations (Choi et al., 2020).

Conversely, focusing on antagonist muscles during dynamic movements could provide clues to understanding human motor control during the application of assistive forces. Notably, the role of the joint movement is not only to exert force; it is also important to move the peripheral part of that joint smoothly and accurately to the proper position, a process which is regulated primarily by the antagonist muscles (Lewis et al., 2010; Hardesty et al., 2020). Considering that the motor control is modified during movement under assistive power, it is hypothesized that antagonist muscles contribute more, particularly in the latter parts of the joint movement.

Consequently, this study focused on submaximal weightlifting (stopping at a targeted height) by elbow flexion and investigated the differences in muscle activity and joint dynamics under assisted and unassisted conditions.

METHODS

Participants

Eight healthy young adults (4 males and 4 females, age: 24.6 ±1.5 years, height: 167.8 ±7.1 cm, weight: 61.6 ±13.1 kg) participated in this study. All participants were right-handed. Before the experiments, written informed consent was obtained from all the participants. This study was also approved by the ethics committee of the Faculty of Design, Kyushu University (Approval number 474).

Experimental Setup

A 1-DOF robotic arm was developed to provide an assistive force to participants during elbow flexion. The robotic arm comprised a servo motor (whose rotational axis could be adjusted to align to the participant's elbow joint), and an aluminum beam that could be attached to the participant's wrist. Compliance control was used to regulate the assistive force based on a targeted angle shown to the participant and the current position of the robotic arm. Here, the spring behavior was used to calculate the assistive force to be provided by the robotic arm, expressed as follows:

$$M_{assist} = K\left(\theta_{target} - \theta_{arm}\right) \tag{1}$$

where *M_assist* denotes the assistive force generated by the robotic arm, *θ_arm* denotes the rotational angle of the robotic arm, *θ_target* denotes the targeted angle shown to the participant, and *K* refers to the stiffness coefficient.

The stiffness coefficient determines the compliance of the arm. Moreover, the larger the difference between the targeted angle and the arm angle, the stronger the assistive force provided is. A stiffness coefficient of 0.2 N m deg^{-1} was used in this study.

Procedures (Tasks)

Participants lifted weights (equivalent to 15% force of maximal voluntary contraction [MVC] during isometric elbow flexion at 90°) with and without assistive force using the aforementioned assistive device, in a sitting position. A monitor placed in front of the participant showed the initial, endpoint, actual, and reference positions of the wrist. The initial and endpoint angles of the elbow joint were set to 40° and 135°, respectively (the elbow in full extension being set to 0°). Participants were instructed to begin elbow flexion when a "start" cue sounded, continue elbow flexion with reference to movement of the reference position, stop flexion at the endpoint position, and maintain the position for 3 s. The reference position was programmed to start moving from its initial position on the "start" cue and stop at the endpoint position after exactly 1.1 s. For the with assistive force condition, the targeted angle of the robotic arm was set to be 0.1 s ahead of the reference position shown to the participant, which creates a resultant assistive force. Each participant performed six trials consecutively under each condition. The order of the conditions was counterbalanced.

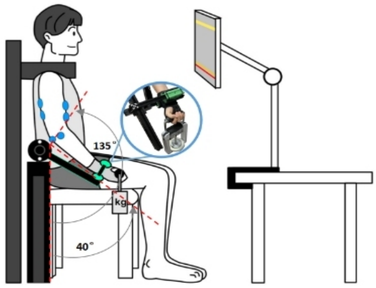

Figure 1: Schematic diagram of the assistive device.

Measurements

During the task, the surface electromyography (EMG) activity of the biceps brachii (BB)—as the primary working muscle—and the triceps brachii (TB)—as the antagonist muscle—was measured using an analog-to-digital converter with a bio-amp (ADInstrument, PowerLab 16/30, ML880,Australia). The mean values of the rectified EMG before and during the elbow flexion process from three of the six trials were calculated and normalized as a percentage of the EMG at the maximal voluntary contraction ($\%MVC_{BB}$ and $\%MVC_{TB}$, respectively). Additionally, the level of the muscles' co-contraction (CC_{ratio}) during the elbow flexion was calculated using the ratio of $\%MVC_{TB}$ to $\%MVC_{BB}$.

Statistical Analysis

For the mean values of $\%MVC_{BB}$ and $\%MVC_{TB}$, a paired-t-test was used to compare the results under the assisted and unassisted conditions.

RESULTS

Figure 2 shows the temporal changes in the average values of all measured parameters under both conditions. Evidently, the elbow joint begins to flex slightly later than the sounding of the "start" cue and the peak velocity of flexion occurs approximately 0.5 s after the "start" cue for most participants. However, the assisted condition exhibits a greater peak velocity than the unassisted condition. Under the assisted condition, the peak torque is also evident at the same time. As the elbow flexion stops, the unassisted condition exhibits a smooth stop, whereas the assisted condition shows the average elbow joint angle to be slightly higher than the endpoint target—that is, early arrival at and/or overshooting the endpoint position are evident in most participants.

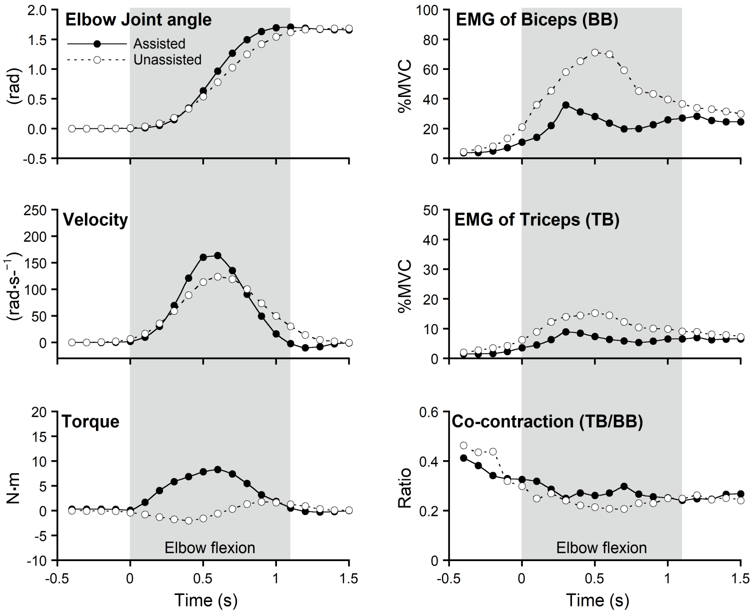

Figure 2: Comparison of temporal changes in average values of each measured parameter under the assisted and unassisted conditions.

The %MVC was lower under the assisted condition than under the unassisted condition for both the BB and TB from before the start to the end of the elbow flexion. Under the unassisted condition, the %MVC of both BB and TB peak at the same time as the peak in the elbow angular velocity (at approximately 0.5 s). However, under the assisted condition, they occur slightly earlier than under the unassisted condition (at approximately 0.3 s). After the peak, the %MVC of both the BB and TB slow down under both conditions; however, only under the assisted condition, the %MVCs increase slightly again before the elbow flexion stops. Furthermore, the decrease in $\%MVC_{TB}$ is smaller than that in $\%MVC_{BB}$, resulting in a clear peak (at approximately 0.7 s) in the CC_{ratio}.

Table 1 presents the average %MVC of the BB and TB during elbow flexion (0 to 1.1 s) with and without the assistive force. Both the BB and TB exhibit considerably lower average %MVC values in the assisted condition than the unassisted condition.

Table 1. Average %MVC during the elbow flexion.

	%MVC of EMG (%)		Reduction rate (%) (U-A)/U	t-test (A) vs. (U)
	Assisted condition(A)	Unassisted condition (U)		
Biceps brachii	24.6± 9.1	51.8±19.2	51.2±13.6	$p < 0.01$
Triceps brachii	6.6±2.3	11.9±5.0	43.8±8.4	$p < 0.01$

DISCUSSION

The force provided by the robotic arm reduced the average %MVC during elbow flexion by 51.2% and 43.8% in both the biceps and triceps muscles, respectively (**Table 1**). Although it can be difficult to calculate what percentage reduction in the %MVC could be expected from the mechanism of the assistive device used in this study, it is evident that the assistive force of this device was effective in reducing muscle activity. Conversely, the effect of the assistive force could also be regarded as the difference in the EMG of the BB and TB between the solid line with closed circles and the dashed line with opened circles shown in **Figure 2**; however, such differences depend on the time phase of the elbow flexion movement. Consequently, when discussing the effect of the assistive force on isotonic muscle contraction, it is necessary to divide it into specific time periods.

Immediately after the start of the movement, $\%MVC_{BB}$ was lower than under the assisted condition in the non-assisted condition, probably because the participants learned how the assistive force was provided through prior rehearsals and suppressed muscle activity in advance. When the starting joint movement was initiated upon the "start" cue, the EMG started to activate prior to the start (Aruin et al., 1998; Bruttini et al., 2016). Because the %MVC was low (even during the pre-start phase of the assistive condition), it is evident that the joint movement was planned with an expectation that assistance would be provided.

During the middle phase of the elbow flexion, the %MVC of both muscles and the torque increased before decreasing under both conditions. That is, the workload on the working muscles was at its maximum at around this time whilst lifting the weight and the torque from the device was well regulated based on the temporal variation of its workload. However, the assisted condition exhibited an earlier onset of the decrease (i.e., peak) than the unassisted condition. This implied that the assistive force was effective in reducing muscle activity after the peak. Interestingly, the rate of %MVC reduction—or the effectiveness of the assistive force—fell around that timing (**Figure 3**). This implied that there was some delay before it was successfully used for the assistive force, as it took some time to perceive it and modify the motor control strategy to adapt it.

During the deceleration phase, inertial forces were also acting, and the moment arm was shortening; consequently, the required muscle activity was also reduced (Gribble et al., 2003). Indeed, a decrease in the $\%MVC_{BB}$ was evident under the unassisted condition. However, under the assisted condition, the antagonist muscle (the triceps in particular) exhibited a smaller decrease, resulting in a higher co-contraction index during the deceleration phase. In this study, the participants were instructed to stop the joint movement at a targeted position, suggesting that the triceps muscles were more active in generating some resistance to the assistive force and increased their co-contraction to stop at a precise position (Lewis et al., 2010; Komi et al., 2000). Nevertheless, the early arrival and overshooting of the endpoint target, despite being complemented by such motor control, suggests that the participants struggled to stop smoothly.

Limitations

This study examined only one combination between levels of a specific workload and assistive force during a lifting task, which was performed only by elbow flexion with one degree of freedom. Additionally, there are many different methods of controlling the assistive force for dynamic joint movements, and different parameters must be set for each. The findings of this study could be influenced by these factors.

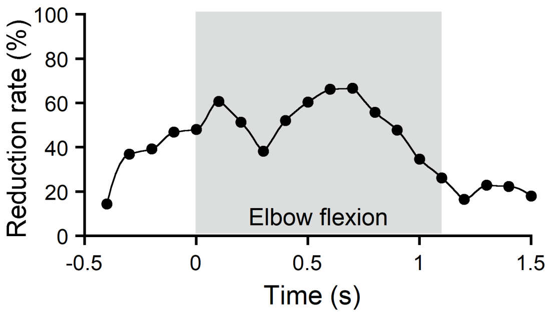

Figure 3: Temporal changes in the reduction rate of $\%MVC_{BB}$ under an assist force (calculated based on the data presented in Figure 2 (EMG of biceps)).

CONCLUSION

In this study, it was evident that under the assisted condition, the reduction of muscle activity of the agonist and antagonist muscles and the precision of the joint movement were controlled based on the respective phase of elbow flexion.

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