On the Well-Timed Assistance in Power-Assisted Sit-to-Stand Movement

Haisong DONG *, Kojiro MATSUSHITA **, Tomoyuki YAMAMOTO ***,*, and Hiroshi ISHIKURO *

Abstract: Many human augmentation devices have been developed in the past few decades, but lots of them neglected the importance of well-timed assistance, which commonly leads to problems like lowered performance or interference with user’s movement. In this research the authors focused in depth on the timing issue of powered assistance. As a pilot study for the proof of concept, the authors hypothesized that different timing of assistance may greatly affect the efficiency of movement for power-assisting devices, and verified the hypothesis through human experiment on sit-to-stand (STS) movement. By measuring the electromyogram (EMG) of lower limb muscles, the authors firstly confirmed the effectiveness of assistance, then compared the effect of assistance timing with other frequently investigated determinants of STS movement, and evaluated the efficiency of movement under different timing conditions. The results demonstrated the importance of timing in powered assistance, and showed that, rather than the common practice of providing assistance after the onset of movement, which is adopted by most traditional proportional-EMG-controlled human augmentation devices, it may improve the efficiency of movement for at least half of the subjects simply by adopting an earlier (before or at the same time of movement onset) but optimal timing for assistance. As a preparation for future works, the authors also quantitatively analyzed various early timing conditions, and the result indicated that if the authors could realize appropriate movement prediction mechanism, the performance of assistance may be improved further. Considering the generality of timing issue in many related works, these results could lead to a new direction of research on performance improvement of human augmentation devices.

Key Words: exoskeleton, timing, well-timed assistance, sit-to-stand movement, EMG.

1. Introduction

In the past few decades exoskeletons have gained increasing popularity as human augmentation device. However, previous researches [1],[2] primarily focused on two aspects. First, enhancing device’s loading capacity by employing high power actuators or complicated mechanical designs; second, the control of exoskeleton as an application of machine learning problem for which only the bio-signal classification and pattern prediction rate are concerned [3],[4]. The timing of assistance, though an important aspect, has been more or less neglected. Many of the existing exoskeletons employed the proportional myoelectric control scheme [5]–[9], in which the assistance was provided according to the measured electromyogram (EMG) of involved muscles of a certain movement. Though it is intuitive and can be readily implemented, since the detection and processing of EMG signal usually follow the movement execution, this method has a critical limitation that most of the time the assistance can only be provided at a fixed timing that is delayed with regard to the movement onset [7]–[9]. Such external support for the movement may not always be desired by the user as it could conflict with the normal movement patterns. As a result, for many exoskeleton prototypes [9]–[11] it was reported that the suits can easily hinder the movement of user, which also reduces the effect of assistance or even causes discomfort for the subject.

Only recently the actuation timing started to gain attention and some works showed that, once the power assistive device is actuated in a well-timed manner, it is actually possible to improve the overall efficiency of the target movement without extra cost. A recent result from Malcolm et al. [12] suggested that a plantarflexion-assisting exoskeleton can maximize the metabolic cost reduction at a proper actuation timing. It outperformed the other works [13] where inappropriate-timed assistance was provided but no actual metabolic benefit can be obtained. This research shows that the actuation timing issue is indeed worth being considered more seriously. Thus, it may be necessary to study the effect of various timing conditions in order to optimize the performance of human augmentation devices.

However, it is worth mentioning that in practice exoskeletons have to deal with unpredictable circumstance and multi-tasking, rather than just assist reciprocating movements like walking. For tasks that require frequent change between different movements and tasks that are composed of a single movement but only last a short period of time, the initiation of every movement can be particularly important. Therefore, this study specifically aims to investigate the impact of timing on assistance of movement initiation. And the authors expect to integrate the concept with other techniques for fully movement
support on a neural-signal-based and more human-friendly exoskeleton for practical scenario at last. In this paper, as the very first stage of the project and as a proof of concept, the authors tried to demonstrate the necessity of optimal timing assistance. The authors hypothesized that:

1. Timing of assistance may greatly affect the efficiency of target movement.
2. Assistance at the same time or before the onset of movement may effectively improve the movement efficiency.

These hypotheses were verified by the result of a controlled human experiment on power-assisted sit-to-stand (STS) movement (Fig. 1). The result indicates the importance of actuation timing in powered human augmentation devices and the feasibility of utilizing timing for performance improvement.

2. Methodology

2.1 Task

The sit-to-stand (STS) movement was selected as the task. It is an appropriate task to be investigated because STS is one of the most frequent activities people do in daily life and well-studied [14]. The authors may also readily generalize the result to some similar movements that many exoskeletons aim to assist, such as squatting and lifting.

2.2 Hardware

A specialized chair was built as the experiment platform (Fig. 2). Four air cylinders (SMC®CM2B20-50) were installed beneath the seat with 1MPa air supplied by a compressor (JUN-AIR®6-25), and controlled by a solenoid valve (SMC®VQZ1321) synchronously. It can be calculated from the specifications that the exerted force is about 264N per cylinder. The lifting of seat, as the assistance in the experiment, lasts 500ms. No constraint was applied to the subjects for fixation. The result is thus purely dependent on the effect of assistance and is irrelevant to the physical constraints that other human augmentation devices usually have.

Regarding the selection of actuator, the authors were aware of the better responsiveness of electric motors, which might be very suitable for current task, but air cylinders were employed for these considerations:

1. In this study the authors are trying to verify whether a different timing condition can possibly improve the performance. For this purpose, high responsiveness is not required. Therefore, air cylinder is sufficient for current stage.
2. Compared to existing human augmentation devices, adopting well-timed assistance might achieve a comparable performance yet no extra cost on high-end actuators is needed. With air cylinders the authors tried to establish such a system that is more affordable but without compromising performance.

2.3 Sensing

EMG sensors (bipolar electrodes) were placed on the chosen muscles (Vastus Lateralis, Biceps Femoris, Tibialis Anterior) following the guidelines [15]–[17] for repeatable and more accurate estimate of surface electromyography (sEMG). The raw data was fed to National Instruments®USB 6229 BNC data acquisition unit at 2kHz sampling frequency as suggested by [17] and smoothed by a simple moving average algorithm with a cutoff frequency of 4.99Hz. For more precise calculation of timing, an accelerometer (Kionix®KMX52) was also installed on the seat so the activation timing of air cylinders and the standing and sitting timing can be recorded for synchronization.

2.4 Scenario

Ten male subjects (average age: 24.60 with an SD 2.72, average weight: 61.70 kg with an SD 5.91 kg, average height 170.50 cm with an SD 8.05 cm) participated in this experiment. They were instructed to repeat the STS movement under different conditions on the customized chair. The movement was finished at self-selected speed unless it was conducted in the “fast movement” condition. A stack of wood plank was placed under the feet of subject to adjust the height of ground for shorter subjects, so the STS movement can always be performed in the most comfortable and natural way as in daily life. The experiment started after a training session of 10 minutes.

2.5 Main Experiment

In the main experiment, the authors tried to show that assistance can help improve movement efficiency and that such effect may be greatly affected by different timing conditions. To evaluate if the impact of timing is meaningful for the development of human augmentation devices, the authors further compared other determinants of STS movement which are closely related to the framework design of power-assisting system. Therefore, 4 variables were considered: the timing of assistance, the speed of movement, the foot position and height (Table 1). EMG signals of the lower extremity muscles (Vastus Lateralis, Biceps Femoris, Tibialis Anterior) were used for accurate estimate of surface electromyography (sEMG).

Experimental procedures:
1. Decide the variable to be examined.
2. 10-second unassisted calibration.
3. (a) Subject performs STS movement under a specific condition of that variable.
   (b) Subject sits down to standby position.

Fig. 1 The schematic diagram of power-assisted sit-to-stand movement.

Fig. 2 The experimental platform.
For advanced assistance condition it is more difficul-
ty perceived the activation of the seat, which in fact pushed
against their hips. Thus, the intervals between air cylinders ac-
tivation and movement onset were actually determined arbitrarily
by the subjects.

Since the moment of the movement onset is defined as time
0, the advanced assistance event corresponds to negative timing
value and the delayed assistance event corresponds to positive
timing value. Though the timing is continuous from advanced
assistance to delayed assistance conditions, the authors man-
aged to select 4 discrete conditions as representatives for quali-
tative analysis, which were the advanced assistance (in advance
of movement onset within an arbitrary range of time), simulta-
neous assistance (at the same time of movement onset), 100ms-
delayed assistance (100ms after movement onset) and 300ms-
delayed assistance (300ms after movement onset), in the order of
timing sequence.

The performance variations obtained under different condi-
tions of all tested variable (height, speed of movement, foot
position and timing) were evaluated and compared. The max-
imal difference of EMG levels were calculated by (1) and (2)
for EMG peak and integral, respectively.

\[
D_{\text{peak}} = \max_{i \in \text{V}, j_1 \neq j_2} |P_{ij_1} - P_{ij_2}|, \quad (j_1 \neq j_2) \quad (1)
\]

\[
D_{\text{integral}} = \max_{i \in \text{V}, j_1 \neq j_2} |I_{ij_1} - I_{ij_2}|, \quad (j_1 \neq j_2) \quad (2)
\]

\[V = \{\text{Height, Speed, Foot, Timing}\}\]

\[C_{\text{height}} = \{\text{Bottom, Top}\}\]

\[C_{\text{speed}} = \{\text{Normal, Fast}\}\]

\[C_{\text{foot}} = \{\text{Wide, Closed}\}\]

\[C_{\text{timing}} = \{\text{Advanced, Simultaneous, Delayed}\}\]

The difference is denoted by \(D\) while \(P\) and \(I\) are the mean value
of normalized EMG peak level and integral level across trials,
respectively.

The maximal difference of a variable among all conditions
shows how greatly this variable can affect the movement effi-
ciency. Therefore, by comparison of this quantity the authors
may find if timing is as important as other variables in terms of
movement efficiency.

Since the authors also argued that, rather than the traditional
practice of providing delayed assistance all the time, early
assistance may effectively improve movement efficiency, the
comparison of the performance among different timing condi-
tions is also a necessary part of the result in order to determine
the optimal actuation timing.

2.6 Supplementary Experiment

After showing the effectiveness of assistance (as the Sec-

<table>
<thead>
<tr>
<th>Variables</th>
<th>Meaning</th>
<th>Conditions</th>
<th>Assistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>Height of seat.</td>
<td>1. Bottom (unrisen seat)</td>
<td>Unassisted</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Top (risen seat, 5cm higher)</td>
<td>Unassisted</td>
</tr>
<tr>
<td>Speed of movement</td>
<td>How fast does the subject perform STS movement.</td>
<td>1. Normal (self-selected)</td>
<td>Unassisted</td>
</tr>
<tr>
<td>Foot position</td>
<td>Distance between two feet.</td>
<td>1. Wide (25 ~ 30 cm)</td>
<td>Unassisted</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Close</td>
<td>Unassisted</td>
</tr>
<tr>
<td>Timing of assistance</td>
<td>The timing of provided assistance with respect to the STS movement.</td>
<td>1. Advanced</td>
<td>Assisted</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2. Simultaneous</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3. Delayed</td>
<td></td>
</tr>
</tbody>
</table>

(c) Repeat (a) ~ (b) till 15 trials.
5. Repeat the procedures 3 and 4 for every other condition(s).
   The default movement setting is unassisted, normal speed
   with widely separated feet and standing from bottom position.
   Only one variable was tested each time while the other variables
   remained in the default condition throughout the session.

It is worth mentioning that as an extensively-explored move-
ment, miscellaneous determinants have been studied in previ-
uous works [18]. Among them, the authors selected these vari-
ables for performance comparison for the following reasons:

1. The height of seat and the foot position essentially rep-
   resent the status and posture of body. They may indicate
different joint angles and center of gravity (CoG) of body
   that leads to distinct requirements for torques and forces
   in joints even for the same movement. If it can be demon-
   strated that the timing of assistance has a comparable ef-
   fect as these variables the authors may formulate such ef-
   fect in terms of torque/force offset and use it to reduce
   muscular effort quantitatively.

2. The speed of movement affects the EMG levels consider-
   ably. For example, from the experimental results the au-
   thors obtained that the EMG peak level of fast STS move-
   ment is approximately 22% higher than in normal speed.
   Meanwhile for assisted STS movement, as the seat is lifted
   by four air-cylinders, the subjects are actually forced to
   perform the movement faster in order to stand up from the
   rising seat. If it can be shown that appropriate actuation
timing can reduce the EMG level even in such fast move-
ment, the result may further demonstrate its effectiveness.
The timing of assistance can be divided into three categories:
advanced, simultaneous and delayed assistance, as the assis-
tance can be provided before, at the same time or after the STS
movement onset, respectively.

The control of simultaneous assistance and delayed assis-
tance requires the synchronization of movement onset and the
actuation timing. Thus, the authors provided 3-second count-
down prompts while playing a “beep” tone every second on the
experimental computer, and asked the subjects to perform the
movement when they saw the prompt “Start!” at the 4th second.
This moment was regarded as the onset of this STS movement.
Then the seat would rise to support the movement at the timing
the authors set with respect to the onset.

For advanced assistance condition it is more difficult to de-
term the precise timing of actuation, because the assistance
is provided prior to the movement onset but the moment of
movement initiation is unknown beforehand. For qualitative
study, the authors designed the experiment as a stochastic pro-
cess where the subjects were required to stand after they subjec-

Table 1 Investigated variables.
tion 3.1 will show), the authors found that timing of assistance could be a crucial determinant of STS movement, and, to the contrast of traditional practice of providing delayed assistance, early (advanced and simultaneous) assistance demonstrated the potential of performance improvement. However, for advanced assistance this result only reflected the averaged effect of a wide range of arbitrary advanced timing. Therefore, the authors conducted a supplementary experiment to quantitatively examine the advanced timing condition for potential further performance optimization. Again, since the advanced timing cannot be determined or measured beforehand, post-hoc analysis was adopted.

Experimental procedures:
1. 10-second unassisted calibration.
2. (a) Assistance is provided.
   (b) Subject performs STS movement after tactile feeling of assistance.
   (c) Subject sits down to standby position.
   (d) Repeat (a) – (c) till 20 trials.
4. Repeat the procedure 2 for one more set.

For each trial, the authors may define the advanced timing as the span from the timing of air cylinder actuation to the starting point of the movement. This enables mapping of the advanced timing of each trial to the corresponding EMG level. By repeating this process the authors obtained the EMG level distribution along the timing axis. Then the authors divided the range of advanced timing into several subintervals to look for an optimal actuation timing interval, defined as the subinterval with the minimal average EMG level. The authors define the optimal advanced timing interval as the interval for which if the assistance is provided within this interval’s range of timing, the chance to reduce the muscular effort is the highest.

In this study the subinterval selection was manual because of the vagueness of data clusters boundaries. The subintervals were selected by the rules that the length of each subinterval has to be from 100ms to 300ms and each subinterval should include sufficient data points (greater than 7 in current configuration). Since the data distribution was arbitrary, certain timing intervals without sufficient data points were skipped.

Then the optimal performance of advanced assistance was compared with the average performance of advanced assistance. The reduction rate can then be calculated by (3) and (4):

\[
\text{Peak red.} = \frac{\text{aver.EMGPeak} - \text{opt.EMGPeak}}{\text{aver.EMGpeak}} \quad (3)
\]

\[
\text{Int. red.} = \frac{\text{aver.EMGInt.} - \text{opt.EMGInt.}}{\text{aver.EMGInt.}} \quad (4)
\]

The rate suggests how much improvement it can achieve through controlled advanced assistance.

2.7 Evaluation Method

EMG signal was used as an indicator of muscle activation. Though muscles of quadriceps (Vastus Lateralis, VL), hamstring (Biceps Femoris, BF) and lower leg (Tibialis Anterior, TA) were all measured, since the quadriceps is dominant [19]–[22] over others in this squat-like movement, only the results of muscle VL will be presented here for performance evaluation.

Calibration (repeating the task movement without assistance continuously for 10 seconds) was conducted before each session to obtain the information of maximal voluntary contraction (MVC). The MVC was used for normalization of the EMG signal obtained during the experiment. Thus the EMG levels were represented by a percentage with regard to the reference EMG voltage of MVC. In EMG-level-based analysis, two types of indicators were compared:

1. The highest peak of normalized EMG level across the duration of an STS movement, which indicates the maximal muscle activation level of this period of time.
2. The integral of the normalized EMG level over the duration of an STS movement, which indicates the overall effort the subject applied on the muscle [23], or how much fatigue it accumulated [24]. This is calculated by adding up the normalized percentage value of each sampling point within the movement duration. It can be regarded as the accumulated EMG percentage value per STS movement cycle.

For both, lower value represents less work, which suggests the corresponding condition is more effective for reducing user’s effort and thus it is preferred because the movement can be executed more efficiently.

In order to calculate the duration of each STS movement, the authors firstly set the minimal threshold of effective EMG signal as 10% of MVC to eliminate noise. Then for effective data points, the authors defined the starting and end point of an STS movement as the instant when the normalized EMG level reaches or falls to 20% of the highest peak value of the interval delimited by the accelerometer signal, respectively. Now the integral can be calculated as the sum of the EMG level over the movement duration. However, it is worth mentioning that this starting point of movement is only used for calculation of EMG integral and timing in post-hoc analysis but does not correspond to the physiological onset of movement, which occurs about 100ms earlier. Since in EMG data the latter is not always differentiable from the non-effective signal, the authors did not use it for calculation.

3. Results and Discussion

3.1 Main Experiment

3.1.1 The effectiveness of assistance

Figure 3 depicted the averaged maximal EMG peak and EMG integral levels of 10 subjects with simultaneous assistance, which were all normalized to their corresponding unassisted performance (denoted by the dashed line on 100% level). It may be noticed that for maximal EMG peak 8 out of 10 subjects showed improved performance as they all successfully reduced the muscle activation level. T-test indicated that the performance difference was significant (p < 0.05) for subject No.1, 2, 3, 7 and 9. On the other hand, as a device aiming to support long-term work, for the more important indicator, EMG integral, 9 subjects benefited from assistance and except for subjects No.8 and 10, the performance of all the other 8 subjects showed significant difference (p < 0.05).

This result suggests that assistance provided by actuated chair may effectively improve the efficiency of STS movement in general.

3.1.2 The effect of timing

The authors then compared the performance variations of different variables under each condition using (1) and (2). In Fig. 4
the authors showed the maximal difference of EMG levels of the four variables. The results have also been averaged across 10 subjects and normalized with respect to difference among height conditions (red dashed line).

Many studies [25],[26] have showed that for STS movement the determinants such as the height of chair, the foot position and the speed of movement can affect the performance of subject to a considerable extent as they vary. Our results indicated that the timing of assistance may be at least as important as other involved determinants.

3.1.3 Optimal timing

In this section the authors present a performance comparison between different timing conditions when assistance was provided. For every subject, the normalized EMG levels were averaged for 15 trials of movement. On account of individual difference, for the convenience of comparison the authors standardized the values of three other conditions with respect to the value of simultaneous assistance condition, of which the corresponding EMG level was set to 100% as the reference. Figure 5 depicted the results of EMG peak and EMG integral. The horizontal axis labels “Adv”, “Sim”, “D100” and “D300” represent for advanced, simultaneous, 100ms-delayed and 300ms-delayed assistance, respectively.

According to the EMG peak evaluation criteria, 6 subjects obtained optimal performance under advanced or simultaneous conditions, while for EMG integral 5 subjects reached their optimal performance also with early assistance.

From this result the authors found that the optimal performance occurs at advanced assistance or simultaneous assistance condition for at least half of the subjects. This means the traditional approach of delayed assistance may have lost more than 50% of the potential of further improvement. In other words, although the effectiveness of delayed assistance cannot be denied, the necessity of advanced or simultaneous assistance should not be ignored either. In addition, for some subjects as the assistance was delayed to later stage (300ms-delayed) of movement, for many trials the assistance was not able to provide any substantial benefit because it could barely catch up with the speed of subject who felt like having performed STS movement without any assistance at all.
Regarding the reason why some subjects obtained better results with delayed assistance, it might be related to their initial posture variation. Although previous works showed that initial posture may not significantly affect overall performance of STS movement [27],[28] and will not lower reproducibility of experiment [29], they also noticed that different initial postures may lead to considerably different timing of movement preparation and execution [28]. For subjects who tend to constantly adjust initial posture, such variations can be very critical in the experiment as the interaction time between subject and seat is very short so it is highly sensitive to difference in timing. However, further experiment is needed in order to verify this hypothesis.

Moreover, since the precise timing of advanced assistance cannot be controlled directly, the comparison here basically demonstrated the performance with advanced assistance in general. If the optimal advanced timing interval can be selected (as the supplementary experiment can manifest), the result may be even more favorable for advanced assistance.

The result revealed the fact that providing assistance in early stages of movement is feasible for efficiency improvement, though it may not be applied to all the subjects.

### Supplementary Experiment

The authors selected optimal advanced timing intervals for each subject and obtained the EMG levels within these intervals (An example of data point distribution of subject No.3 is illustrated by Fig. 6. Time 0 indicates the onset of movement). Table 2 showed the performance improvement for advanced assistance by adopting the optimal timing using (3) and (4). When optimized based on the EMG peak value, an average of 10.33% additional reduction can be achieved and when optimized by EMG integral, the reduction rate is 7.64%. The effect can be demonstrated more intuitively in Fig. 7. Dashed line at 100% indicates the average performance.

Figure 8 depicts the optimal advanced timing interval the authors found for 10 subjects. The horizontal dashed dotted line on each point delimited the range of this interval and the vertical error bar indicates the standard deviation of the corresponding EMG level (peak or integral) within this interval. Time 0 indicates the onset of movement.

This result is highly subject-sensitive so there is no certain interval that is preferred by the majority of subjects. Besides, for most subjects, the two optimal intervals optimized by peak

<table>
<thead>
<tr>
<th>Subject</th>
<th>Avg. EMG peak (%)</th>
<th>Opt. EMG peak (%)</th>
<th>Peak reduction (%)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>49.29</td>
<td>46.97</td>
<td>4.94</td>
</tr>
<tr>
<td>2</td>
<td>73.55</td>
<td>59.74</td>
<td>23.11</td>
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<td>3</td>
<td>81.56</td>
<td>69.22</td>
<td>17.83</td>
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<tr>
<td>4</td>
<td>65.98</td>
<td>62.43</td>
<td>5.68</td>
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<tr>
<td>5</td>
<td>92.11</td>
<td>87.35</td>
<td>5.45</td>
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<td>10</td>
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<tr>
<td>Average</td>
<td>74.89</td>
<td>68.09</td>
<td>10.33</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Subject</th>
<th>Avg. EMG int. (% per STS cycle)</th>
<th>Opt. EMG int. (% per STS cycle)</th>
<th>Int. reduction (%)</th>
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<td>10</td>
<td>35760.35</td>
<td>32875.68</td>
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</tr>
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</table>

![Fig. 7 The muscle activation levels with optimal advanced timing.](image-url)
and integral do not coincide.

Independent two-sample t-test was conducted and for three subjects their optimal actuation timing intervals showed a significant difference ($p < 0.05$) against every other non-optimal subintervals.

3.3 Optimal Timing Analysis

3.3.1 Acquisition of optimal timing

Although the experiment results indicated the effectiveness of optimal-timing-based assistance, the acquisition of such an optimal timing is not as straightforward. As the results in Figs. 5 and 8 demonstrated, the optimal timing is highly subject-dependent and also shows inconformity if the authors search for it based on different criteria (EMG peak oriented or EMG integral oriented). Moreover, the timing the authors found is only effective for STS movement, and whether it is helpful for other tasks remains unknown. In a word, the optimal timing can be affected by many factors and in the current stage the authors still have no concrete idea on the dynamics behind the results.

For this reason, to obtain the optimal timing for a subject on a certain task, the lack of precise model leads the way to experiment. As the usual practice that many exoskeleton researchers and technicians adopted, an individual calibration procedure before actual operation is inevitable. Various timing conditions, especially early assistance, have to be examined in order to determine the optimal timing to be utilized for a target task.

3.3.2 Adaptation of optimal timing actuation

The interaction between human subject and the machine is rather complicated. As people can design an exoskeleton to learn from the habit of user, the user may also adapt to the human augmentation device along a long-term use. For example, a study on a walking exoskeleton [30] achieved an improved performance each day during a training period of four days. Intuitively, questions like these may be raised: Can a subject gradually adapt to specific actuation timing that is not optimal at the beginning? Or can subjects who prefer to delayed assistance be trained to get used to advanced assistance?

Though the authors currently cannot answer these questions with compelling experimental evidence, in this research it can be observed that, during the 10 minute training session, generally subjects were not used to the assistance at the beginning but all adapted after a while of practice. This change in behavior was manifestation of adaptive behavior. Thus, it may be possible that if the authors extend the training session to several days with advanced assistance, they may end up showing optimal performance under this condition.

4. Future Works

This research revealed the potential of timing based performance optimization for human augmentation device. Whether this timing hypothesis is effective on real exoskeleton requires further experiments. The impact of exoskeleton constraints and its interaction with actuation timing would also be an interesting topic to investigate. For these purposes, a prototype of wearable lower body exoskeleton was developed (Fig. 9). Sensors for physical and physiological data recording, for instance, rate, gyro, angle sensors and EMG electrodes were attached on joints and muscles. Air cylinders are also installed across the upper and lower leg each side for supporting various movements.

Besides, to apply the result the authors discovered in this experiment on actual exoskeleton, in order to realize early assistance, it is necessary to implement a mechanism for movement prediction, which would be the goal for the next stage of this exoskeleton project. Via motion sensors and neural signals, a motion pattern transition model [31] based paradigm will be adopted for this prototype. In addition, a more recent proposal of the authors, which is inspired by previous works on contingent negative variation (CNV) [32],[33], is utilizing external stimuli as a constant prompt for determining the timing of movement onset and combining such data (obtained from EEG) with other EMG information. This technique shows promising potential to serve the task of movement prediction.

5. Conclusion

The authors conducted controlled human experiment to verify the hypothesis that the timing of actuation is a very important determinant that can be used for improving the performance of human augmentation device. Supplementary experiment on optimal timing condition further showed that the adoption of well-timed assistance may outperform the conventional proportional-EMG-based control method. These results suggested a novel direction for optimization of exoskeleton.
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References
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