Objective and subjective evaluation of a passive exoskeleton for upper limbs

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ABSTRACT

The aim of this study was to evaluate the Hapo ms, a passive upper limbs exoskeleton developed to assist workers for tasks with arms in front of the body. Twelve participants had to perform a static task, a manual handling task and a load carrying task two times: with and without the exoskeleton. In all cases subjective (perceived effort in arm and back areas, comfort) and objective (muscular activity, postural balance) criteria were evaluated. Results have shown a decrease in anterior deltoid (-12 to -18% depending of the task) and in biceps brachii (-19% to -33% depending of the task) muscular activity. No significant difference was pointed out in back muscle and postural balance was not significantly perturbed due to the wear of the exoskeleton. Finally, perceived effort reduction was observed during the three tasks (except in back area for task 1). To conclude, the Hapo ms seems well adapted to assist upper arms during tasks with arms in front of the body.

Key words: MSDs, Exoskeleton, Upper limb assistance, EMG, balance test, subjective questionnaire

INTRODUCTION

As society changes with time, so work does. Today many jobs have been automated, but between the ones that are still done by man's hands, musculoskeletal disorders (MSD) are still present [1][2]. Among all the work-related MSDs reported in 2012 in the USA, back and shoulder injuries represented 41.2% and 13.6% respectively [3]. According to the sixth Eurofound survey published in 2017, a similar tendency can be observed in Europe: the most commonly reported MSDs among workers are backache (43%) followed by muscular pains in the neck or upper limbs (41 %) [4].

Work-related MSDs have direct consequences not only for workers (physical and/or psychological problems, precarity…), but also for companies (absenteeism, turnover, loss of productivity, decrease of quality…) [5]. Starting in 2020, the European Agency for Safety and Health at Work (EUOSHA) began a European campaign to raise the awareness of work-related MSDs and the prevention of them in employers, workers and all the stakeholders in the European Economy.

To address some of the issues associated to MSDs, one of the solutions consists in providing the workers Physical Assistance Devices (PAD) such as exoskeletons. Initially developed in rehabilitation or military purpose, innovative solutions have then been specifically developed to answer the industrial needs [6][7][8][9]. Through the past years, different technologies have been investigated by manufacturers: some exoskeletons (the active ones) are working with actuators or engines while the others (the passive ones) are using the energy conservation principle stored up into elastic band or composite springs [10].

Despite the promising benefits of exoskeletons for the users (*i.e.* reducing muscular activity) [11][12][13], other studies have shown these technologies can also lead to discomfort or cause physical troubles [10][14]. Specifically on upper limb exoskeletons, Theurel *et al.* have also pointed out three major limits to previous evaluations [15]. First, most of the studies focused on tasks with the hand over the head but didn't have investigate manual handling tasks with hands in front of the body. Second, a reduction in shoulder muscle activity do not necessarily lead to a decrease in MSDs risk. However, it seems using a PAD for shoulder flexion less than 90° could limit mechanical strain at the origin of tendinopathy at the subacromial level. Third, it is unclear on how exoskeletons have an influence or not in lumbar activity. In addition, the INRS have shown shoulder

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assistance devices can disturb postural balance of the worker, in particular for manual handling of loads less than 5 kg [16].

Since there is no specific standard to refer, exoskeletons should be evaluated within a global approach, considering subjective (perceive effort, comfort…) and objective (muscular activity, balance…) criteria. This paper aims to evaluate a new industrial exoskeleton which have been developed to assist the upper limbs during tasks with the arms in front of the body. In particular, this study takes into account the previously cited limits, analyzing both agonist and antagonist muscles, including the ones which do not benefit from the assistance of the exoskeleton.

PROTOCOL

Participants

Twelve healthy adult subjects (5 women and 7 men), right-handed and without history of neuromuscular disorders have been selected to participate to the study. Respected means and SD for age, height and mass were 30.3 ± 9.9 years old, 172.4 ± 11.1 cm, and 71.0 ± 17.4 kg. The participants were advised not to perform strenuous activities for at least the two days before the experiment to avoid the risk of muscle fatigue. All of them gave their written and oral informed consent prior to the study.

Experimental design

Three representative tasks for upper limbs assistance have been considered during the experiments. Each task has been conducted in a laboratory environment under two conditions: with and without the Hapo ms exoskeleton.

The first one is a static task which replicate working jobs with hands over head. Participants were asked to stay 35 seconds with their arms at 105°, holding 1 kg in each hand. An adjustable tripod rod was used as a reference during the experiments to ensure participants were maintaining their arms at the required angle (Figure 1).

Figure 1: static task with arms at 105°, 1 kg per hand

The second task was representing a manual handling task with hands in front of the body. Participants were facing a table with an electric base adjusted at 5 cm under their sternum height. They were asked to grasp weights (6x 1kg + 2x 2kg) one by one to move them from the left side of the table to the right side and vice versa (Figure 2). This task was performed 3 times with the right hand and 3 times with the left hand.

(a) (b)

Figure 2: manual handling task: 6 x 1 kg + 2 x 2 kg weights to shift from: (a) left to right; (b) right to left

The last task consisted in carrying a 6 kg load between two places (Figure 3). This task was designed to replicate a punctual operation when the operator has to bring a box (tool, items, parts...) to his workspace to continue his job. Participants have to take the load from the table (same height than for Task 2), turn around and go to place it on a 50 cm height seat, 3 m away. They have then to bend down again, retrieve the load and carry it to its initial place on the table. This task was repeated 10 times.

(a) (b)

Figure 3: dynamic task: 6 kg load to carry (a) from a table (b) to a seat 3 m away

Procedure

At their arrival into the lab, participants were welcomed and informed of both the purpose and the protocol of the tests. They could then ask all the questions they had in order to make them confident and relaxed prior to the experiments.

The following step consisted in EMG sensors placement on 6 muscles (anterior deltoid, biceps brachii, pectoralis major, triceps brachii, longissimus and latissimus dorsi) following the SENIAM recommendations [17]. The Maximum Voluntary Contractions (MVC) for each muscle have then been recorded three times during 5 seconds isometric contractions, followed by 45 seconds rest. According to Burden [18], MVC values permit to normalize muscle activity measurements and compare results between participants. Finally, it has been asked the participants to do some trials of each task to ensure they perfectly understood the protocol.

Two conditions were considered during the experiments: with the exoskeleton and without. Both conditions were previously randomized for each participant. A 10 min break was given to the participants between the two conditions to limit any bias related to physical fatigue. In both cases, the three tasks were performed in the same order for all the participants. First the static task with hand over the head, then the manual handling task and last, the load carrying task. Each task was separated by another 5 min break.

Equipment and instrumentation

Exoskeleton

The Hapo ms is a passive, lightweight (1.3 kg) exoskeleton developed by Ergosanté to assist the upper limbs during jobs with the arms in front of the body. This PAD provides an assistance for all work at a vertical arm angle of 0° to 135° and in a horizontal range of 180°. The Hapo ms is constituted of 3 main elements (Figure 4):

- a harness which is wore like a backpack.
- two springs (one for each arm) made of fiberglass composite material.
- two double-interfaces which maintain both the upper arm and the lower arm at the elbow articulation

This exoskeleton has been developed under 2 possible spring stiffnesses. The choice of the stiffness depends of the kind of job (frequency, duration, arm height…), the morphology of the user and its personal preference. During this experiment, it has arbitrary decided to use the softer springs (provided assistance until 4 kg).

Figure 4: lateral view of the Hapo ms. (1) Harness; (2) Springs; (3) double-interface)

Once worn on the back like a backpack, the Hapo ms needs to be fitted to the morphology of the user. Several straps permit to adjust the size of the harness while the height of the springs is adapted to the height of the trunk using telescopic tubes. Double-interfaces are then fastened to upper and lower arms at the elbow level.

Surface electromyography

Surface electromyography (EMG) data have been recorded at a 2000 Hz sampling rate using quadrupole Trigno Avanti sensors (DELSYS) for the three tasks (only on the right side of the body). The transmission of EMG signals was achieved via the internal Wifi network and the data acquisition was performed using EMGworks Acquisition software.

Considering the intent of use of the exoskeleton, it has been decided to analyze muscular activity for:

- elevator muscles of the arm (anterior deltoid, biceps brachii and pectoralis major)
- spinal erector muscle (longissimus)

- antagonist muscles (triceps brachii and latissimus dorsi)

The muscles have been shaved and cleaned with biomedical materials in order to remove sediment and the layer of dead skin, thus minimizing the influence of possible variations in impedance under the electrodes. Electrodes were then placed according to the SENIAM recommendations, which suggest placing them longitudinally and along the fibers of the muscle [17]. Figure 5 shows the EMG sensors placement on the human body.

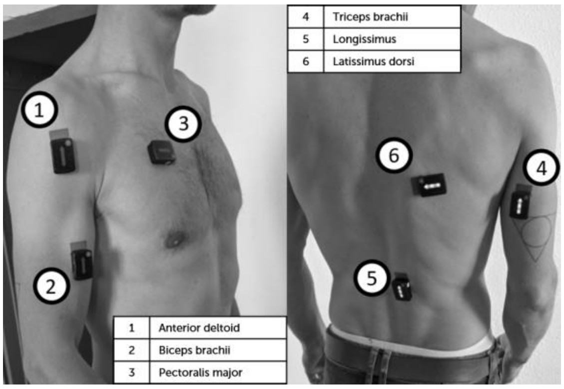

Figure 5: EMG placement

Data processing have been done with a customized script in MATLAB (The MathWorks Inc. Natrick, MA, USA) following three steps. First, raw data were rectified and filtered using a 4 Hz low pass filter (3rd order Butterworth filter). Then, the Root Mean Square (RMS) values were calculated for all the EMG data (MVC test and for the 3 tasks). Finally, EMG activity related to the 3 tasks were normalized to the maximal MVC RMS values.

Force-platform

Previous studies have shown postural balance can be analyzed from the Center of Pressure velocity (COPv) value [19][20][21]. To do so, an AMTI® AGC-O force platform has been used for Tasks 1 and 2 (static tasks). The ground reaction forces and momentum were recorded at a 150 Hz frequency for the x, y and z directions, then low-pass filtered at 5 Hz. Finally, the mean COPv values have been calculated for both tasks, with and without the exoskeleton.

Subjective questionnaire

Two kind of subjective criteria have been considered during the experiments: the perception of the effort (both for upper limbs and for the dorso-lumbar area) and the global comfort. A CR10 Borg scale is commonly used in the literature to evaluate muscular activity perception due to the relationship between the effort (F) and the CR10 measurement (F = CR10 x 10). As for the comfort, participants have to score their perception between 0 (very uncomfortable) and 10 (very comfortable).

Both criteria were evaluated for the 3 tasks and 2 conditions, except for the global comfort which have not been considered in task 1 (not relevant due to the static nature of the task).

Data processing and analysis

Objective and subjective data were analyzed using JASP open-source Software (University of Amsterdam, The Netherland), with significance set at $p < 0.05$. Due to the small number of the population (n = 12 participants), the assumption of normality of a Student t-test was not respected. Therefore, the non-parametric Wilcoxon test have been used for the statistical analysis.

RESULTS

Task1: static task

Three muscular activity measurements were significantly lower ($p < 0.05$) with the exoskeleton: anterior deltoid, biceps brachii and pectoralis major muscles. Results presented in Figure 6 show almost 12%, 26% and 18% decrease for the three muscles respectively.

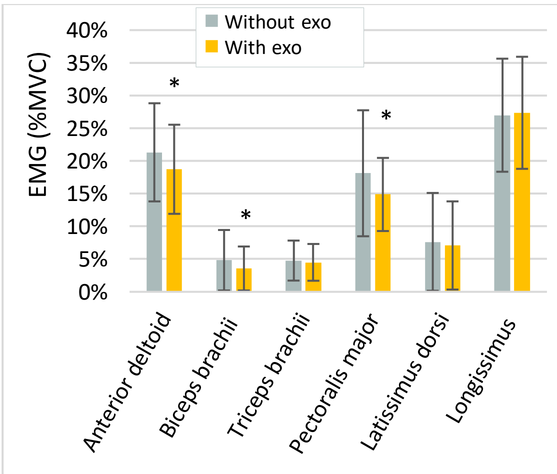

Figure 6: Mean EMG values normalized by the MVC for each muscle, with and without the exoskeleton. Asterisks denote significant differences (p < .05) from the reference condition (without exoskeleton)

COPv results have been analyzed only for 8 participants due to technical issues during data acquisition. Mean values for both conditions (with and without the exoskeleton) were respectively M_{w/o_exo} = 0.0091 m.s^{-1} and $M_{w/\_exo}$ = 0.0086 m.s^{-1} but these results are not statistically significant.

Results in terms of perceived efforts estimated by the participants are presented in Figure 7. The statistical analysis showed that using the exoskeleton help to reduce the perception of effort in upper arms ($p < 0.05$) from a 3.96/10 score (between "moderate" and "strong" perceptions) to a 2.42/10 score (between "weak" and "moderate" perceptions). There was no significantly difference for the effort perceived in back area.

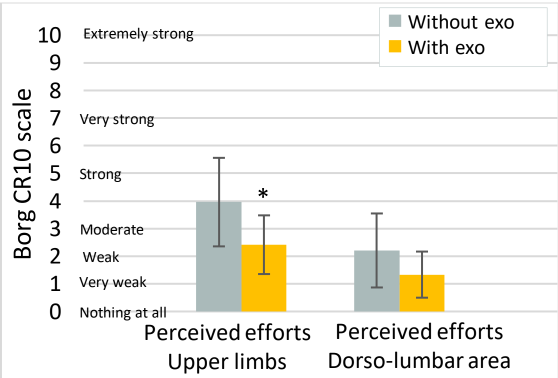

Figure 7: Subjective results for task 1: perceived efforts with and without the exoskeleton. Asterisks denote significant differences (p < .05) from the reference condition (without exoskeleton)

Task 2: manual handling task

For a technical problem, only 11 out of 12 participants have done this task. Concerning muscular activity results, four EMG measurements were significantly lower ($p < 0.05$) during the condition "with exoskeleton" (Figure 8). Anterior deltoid and biceps brachii activity were 16% and 33% lower with the Hapo ms. As for the pectoralis major and the latissimus dorsi, EMG values are -7% and -12% lower compared to the reference condition.

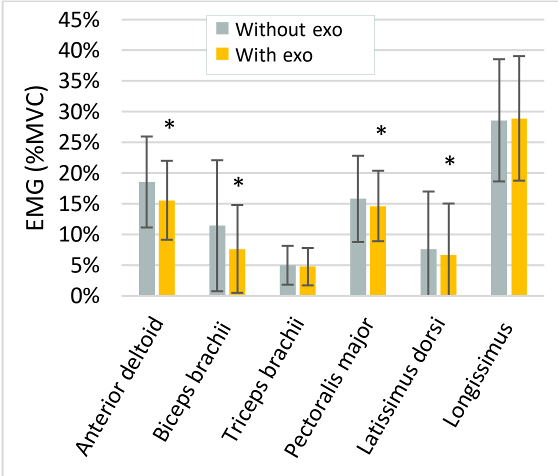

Figure 8: Mean EMG values normalized by the MVC for each muscle, with and without the exoskeleton. Asterisks denote significant differences (p < .05) from the reference condition (without exoskeleton)

The statistical analysis of COPv measurements didn't show a significantly difference when participants were using the exoskeleton or not. In both cases, mean values are M_{w/o_exo} = 0.1212 m.s^{-1} and $M_{w/\_exo}$ = 0.1204 m.s^{-1}.

Subjective results are presented in Figure 9. The effort perceived for both the upper limbs and back areas were statistically lower with the exoskeleton ($p < 0.05$) while this condition was not respected for the perceived comfort ($p > 0.05$). The mean CR10 scores were -27% and -36% compared to the condition without the Hapo ms.

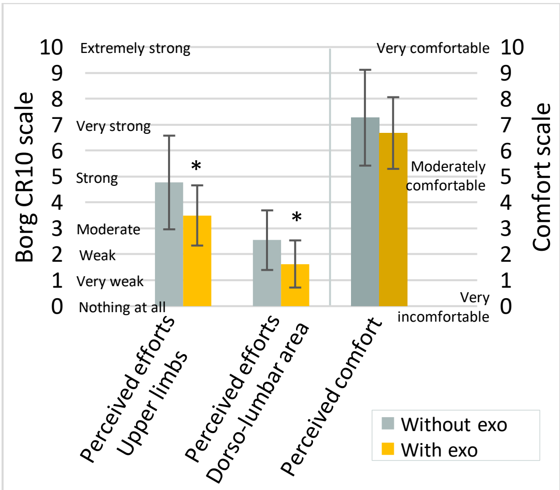

Figure 9: Subjective results for task 2: perceived efforts and perceived comfort with and without the exoskeleton. Asterisks denote significant differences (p < .05) from the reference condition (without exoskeleton)

Task 3: load carrying task

The third task have shown a statistical difference between both conditions only for the arm muscles ($p < 0.05$). Figure 10 presents a 18%; 19% and 7% reduction in muscular activity for anterior deltoid, biceps brachii and triceps brachii respectively when using the exoskeleton.

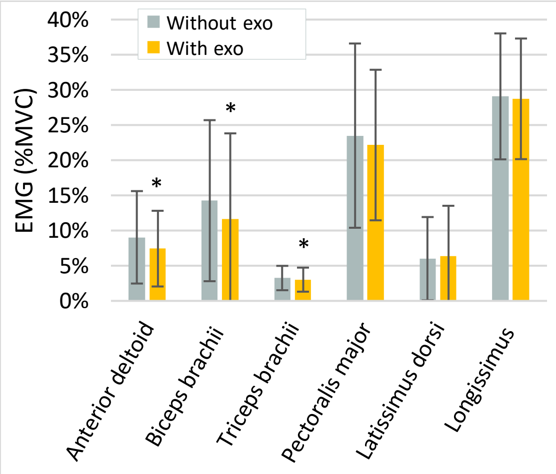

Figure 10: Mean EMG values normalized by the MVC for each muscle, with and without the exoskeleton. Asterisks denote significant differences (p < .05) from the reference condition (without exoskeleton)

The participants perception results in terms of effort and comfort are presented in Figure 11. These subjective criteria were statistically lower when participants were wearing the Hapo ms compared to the condition with the exoskeleton ($p < 0.05$). Mean CR10 values decreased from 3.25/10 to 2.58/10 (21% reduction) for the arm perception, and from 2.83/10 to 1.88/10 (34% reduction) for the back perception. Finally, participants have estimated a general comfort when doing the manutention task 15% lower when wearing the exoskeleton.

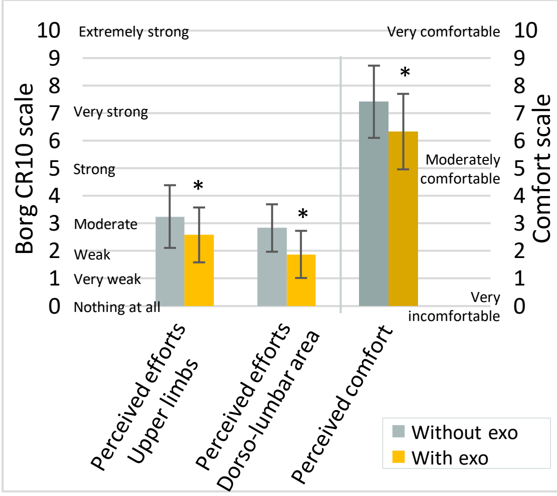

Figure 11: Subjective results for task 3: perceived efforts and perceived comfort with and without the exoskeleton. Asterisks denote significant differences (p < .05) from the reference condition (without exoskeleton)

DISCUSSION

The purpose of this study was to evaluate a passive exoskeleton which has been developed to assist the user during mid-height tasks.

Influence in muscle activity

Results of the present study have shown a significant reduction of both elevator arm muscles (anterior deltoid and biceps brachii) when tasks were performed with the exoskeleton. As for the deltoid, the improvement between both conditions were 12% (from 21.3 to 18.7 %MVC), 16% (from 18.6 to 15.6 %MVC) and 18% (from 9.0 to 7.4 %MVC), respectively for Tasks 1, 2 and 3. As for the biceps, muscle activity was 26% for the static task with overhead arm, 33% for the manual handling task and 19% for the load carrying task.

Similar trends have already been observed in previous studies [22][23][24][25], but shoulder activity values can vary from one study to another depending of the task, the tool mass [26] or the exoskeleton design [27].

In addition, wearing the exoskeleton helps to reduce pectoralis major muscle activity of 18% for Task 1 and 7% for Task 2. As for the third Task, no significant reduction has been observed with and without the exoskeleton (~22 %MVC in both cases). That can probably be explained by the EMG sensor placement on the upper muscle area (clavicular head) which is mainly activated for forward flexion of the arm.

Apart Task 1 which was static, Task 2 and Task 3 comprised respectively left-right and forward-rearward movements of the arm. As a consequence, both agonist (anterior deltoid and biceps brachii) and antagonist muscles (triceps brachii and latissimus dorsi) were solicitated.

In a 2018 study [25], Theurel *et al.* have shown a much higher solicitation of the triceps brachii during lifting (+95%) and stacking (+116%) tasks with the exoskeleton. The authors specified this oversollicitation could be linked to the design of the exoskeleton: energy is accumulated when the arm is extended (compression of the spring), then delivered when the arm is going up (shoulder extention). Knowing that the Hapo ms technology is also based on the spring storage principle (accumulation and delivering of the energy), a similar trend was expected in the present study. The situation is the opposite: there was no significant difference for Tasks 1 and 2 while the exoskeleton helped to reduce triceps activity for Task 3 (-7%). A possible explication is given by the specificity of the task where triceps is arm suspensor, working in synergy with other muscles, in particular when participants have to take and put down the load. As for the latissimus dorsi, the only significant result was observed during the manual handling task. Muscular activity measured here was 12% lower when wearing the exoskeleton, which is in line with Huysamen study [22]

Influence in postural balance

Postural balance is a key parameter which can be influenced by the use of a wearable device such as an exoskeleton. In a previous study [24], Kim *et al.* showed the use of a passive, upper extremity exoskeletal vest increases the center of pressure velocity in the anterior-posterior direction by ~12%. As for the Hapo ms, no statistical difference has been noticed in postural balance during both static and manual handling tasks compared to the condition without the exoskeleton. The difference of results between studies can be explained by the exoskeletons weight: the Hapo ms is 1.3 kg while the one considered in Kim study was 6.5 kg.

Subjective perception

Results have showed a decrease in subjective criteria when participants were using the exoskeleton. Perceived efforts in upper limbs were in line with the EMG data (less muscle activation for anterior deltoid, biceps brachii and pectoralis major). Conversely, perceived efforts in the dorso-lumbar area were not consistent with objective measurements. This is particularly true for task 3 where participants have reported a 34% improvement in back muscle activity while no significant results were observed with EMG data. Three hypotheses could explain this phenomena. First, wearing an exoskeleton could have a contextual effect on participants perception. Second, the Hapo ms could have improve the global perception, so participants felt an assistance in both upper limbs and back area. Third but not very probable, the exoskeleton could have assisted back muscles other than the latissimus dorsi and the longissimus. As for the perceived comfort, a significant difference has been noticed only for task 3. Regarding these results, we could assume the Hapo ms slightly reduced the comfort when participants were walking but not when he is in static position (no displacement).

LIMITS

Three main limits can be pointed out. First, participants were all in good health and quite young (mean age 30.3 ± 9.9 years old), which is not representative of the active working population. Second, the population sample is limited (12 participants), especially when analyzing postural balance results (only for 8 participants for task 2 due to technical issues). Third, participants of the study are Ergosanté Group employees, which may have a slight impact on subjective results only (objective measurements are not affected). This limit has nevertheless been controlled by choosing participants among workers of a subsidiary which is not involved into the exoskeleton development process.

PERSPECTIVES

This study was focused on lab tests performed with the Hapo ms providing a 4 kg assistance. Further tests considering stiffer springs (assistance until 6 kg) will be done following the same protocol as described in this paper. The objective is to have a complete evaluation of the Hapo ms, whatever its assistance (4 or 6 kg).

CONCLUSION

The passive upper limbs exoskeleton evaluated in this study significantly reduce muscular activity for the anterior deltoid and the biceps brachii: these are the main muscles solicited when using the Hapo ms. Shoulder muscles results have showed a 12%, 16% and 18% reduction respectively for tasks 1, 2 and 3, while the improvement was 26%, 33% and 19% for the biceps brachii muscle. No significant differences have been pointed out in antagonist and back muscles activity, neither in term of postural balance. Subjective criteria have shown a good appreciation of the exoskeleton for the participants for all the tasks, with the exception of the comfort criterion which was slightly reduced. To conclude, the exoskeleton evaluated during this study seems well adapted to assist the user during mid-height tasks.

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