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A Study to Determine the Feasibility of Exoskeleton in Climbing Stairs during Load Handling

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ABSTRACT

This paper is to determine the feasibility of exoskeleton in handling motion during climbing a set of stairs. This information is vital in the core design of an exoskeleton system and a part of the build up for a new exoskeleton system named the Shadow-Suit concept. The psychological effect of a foreign object attached to a body limb may have a consequence on the wearer of an exoskeleton, hence affecting the motion especially during overcoming obstacles such as stairs. This foreign object psychological mind set is common among braces wearer and was evident in numerous cases of orthosis wearer. A benchmark of stair ascending motion by the wearer of exoskeleton was set according to motion of the wearer without the assist of any exoskeleton system. The subject endured through several run ascending and descending the stairs while carrying a load over a shoulder strap backpack, assisted by a non-tethered exoskeleton system. Comparison was made in term of the performance of the subject. Performance in this context was defined as the heart beat rate measured in beats per minute and the time taken to complete a cycle of movement measured in second. A t-test was conducted to compare the difference between these values. The result yields a t value of 3.1158 with a 4 degree of freedom for heart beat rate and t value of 11. 9744 with 4 degree of freedom for time difference. These differences indicates that the fatigue level of the subject was delayed over time while using the exoskeleton. However, the time taken for the subject to complete the task elongates. This result suggests the practicality of using exoskeleton in handling materials with a setback in term of the time taken for the subject to complete the motion.

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INTRODUCTION

Robotic exoskeletons and Power Assist Devices (PAD) are designed by various fields most notably military, manufacturing and medical in order to augment human muscle and energy capability. Divided into load-bearing and orthosis, exoskeletons significantly assist humans in performing activities of daily livings (ADLs) in order to minimize the usage of energy and to reduce muscle fatigue and loss of concentration, somewhat unachievable using conventional material handling devices (de Santos *et al*. 2007). Powered anthropomorphic designs work on the principle of most of the load-bearing will be handled by the device (exoskeleton), while transferring the “feel” of the load as a natural, reduced feedback to the wearer, as demonstrated (Kazerooni, 2008) in an exoskeleton design which is named BLEEX. It was inferred by Kazerooni, due to high level of sensitivity of the control module, sensors and actuators, it affects the total robustness of the whole design.

The architecture choice of the exoskeleton designs (either anthropomorphic or non-anthropomorphic) relied heavily on the purpose, nature and the potential user itself. Exoskeleton designs require human anthropometry data, however, kinematics and dynamics. The architecture choice of the exoskeleton designs either anthropomorphic or non-anthropomorphic) relied heavily on the purpose, nature and the potential user itself. Exoskeleton designs require human anthropometry data, however, kinematics and dynamics comprehensive data should be considered as well. When kinematics and dynamics is taken accounted for, the design would become more complex (Raziff and Dian, 2012), especially for anthropomorphic designs, an example where (Zoss, Kazerooni and Chu, 2005) chose to detach from this architecture and made BLEEX a pseudo-anthropomorphic.

In opposition, a non-anthropomorphic exoskeleton provides flexibility with its open design, ability to cater human limb but is not required to be in conformance with it as long as it does not interfere with the wearer’s

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(Zoss *et al*., 2006). The sensitivity level would be significantly lower, with lesser joint articulation to deal with, especially when these two architectures are being non-powered designs. To demonstrate this concept, one can look to this; a simple example of non-powered, non-anthropomorphic load-bearing exoskeleton architecture is a traveler's backpack.

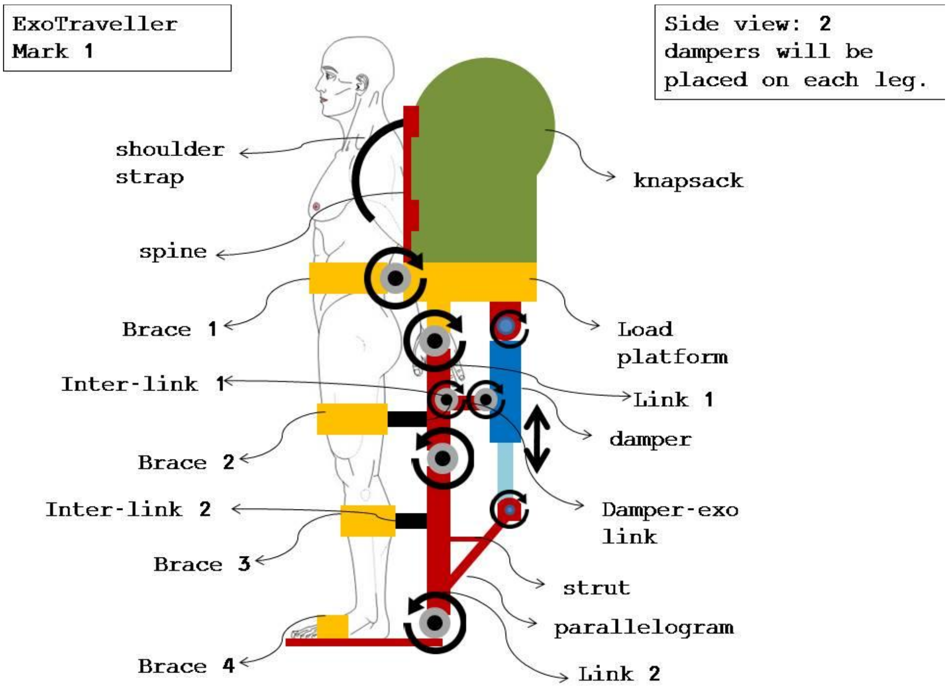
These regions of consideration are important in catering the motion of a wearer of an exoskeleton. A wearer will feel the constraint in motion while wearing an exoskeleton during earlier stage (Rosen *et al*., 2005), similar occurrence to any typical situations such as learning how to drive a car or walking with glasses for the first time. Hence, the design of the exoskeleton must blend well with the human range of motions and articulations. Of course, adhering strictly to true human articulation would increase the complexity of the exoskeleton. For this, the design of an exoskeleton must eliminate the need of human flexibility and built a custom range of motion that is low in Degree of Freedom (DoF) but does not restrict the common movement of a human. These custom ranges should be able to allow the wearer to perform common human simple task such as walking, bending and strafing.

A more complex motion such as climbing a set of stairs requires a combination of two or more of the aforementioned tasks and such an activity would set a challenge to a wearer of an exoskeleton. Due to this difficulty, an experiment was conducted to evaluate the feasibility of an exoskeleton suit of handling material while climbing a short set of stairs. This study was set to observe the level of handling by the wearer of an exoskeleton, designed using lesser articulations and degree of freedom than human's limbs. The measurement considered in this activity is the time taken to complete the task, the energy used, fatigue level and comfort level of the wearer. This paper discusses on the capability and practicality in using an exoskeleton in handling materials (loads) within these capacities. This research is a part of the design and fabrication of a more complex exoskeleton concept named the Shadow-Suit, where it contributes to the understanding of the resourcefulness of the exoskeleton system.

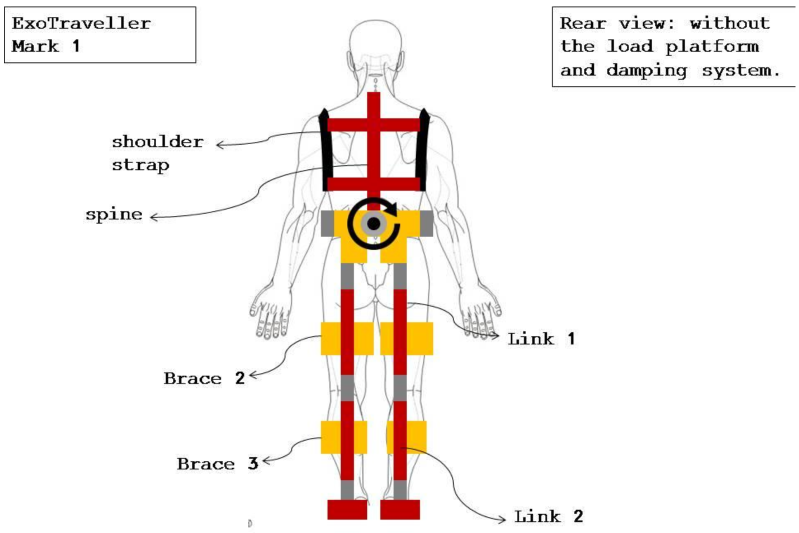
2. The Exoskeleton Design:

This experiment utilizes a non-anthropomorphic exoskeleton with a back support for load bearing, controlled by a wearer's limb and monitored by several personnel including a nurse to monitor the wearer heart activity. For this specific experiment, the exoskeleton was non-powered. The purpose of this so that the exoskeleton will not be tethered, hence maximizing the outcome of the experiment observation result with no interruption from power cords and pneumatic tubings. Only a set of actuator is set to activate in this particular exoskeleton, where a constant volume gas damper is placed between the back support and a parallelogram set on the hind of the shank. The purpose of this constant volume gas actuator is to regulate the load applied towards the back, thus transmitting 75% of the load to the parallelogram towards the ground.

The exoskeleton joints are rotation type, consisting of one dimension bearing type for each of moving joints. These joints are as illustrated in Fig. 1(A and B).



(a)



(b)

Fig. 1: (a) Side view of the exoskeleton indicating rotation of joints (b) Back view of the exoskeleton indicating rotation of joints

Eight rotating joints connecting multiple links, allowing the limbs connected by the brace to move freely as possible to a limited fixed range of motion, thus allowing the wearer to move. This exoskeleton is categorized as a lower extremity, but not exclusively, since the load is partially supported by the shoulder strap and the spine. There is no power cords connected to this exoskeleton making it unpowered but crucially non-tethered. This concept is translated and depicted in Fig. 2 illustrated.

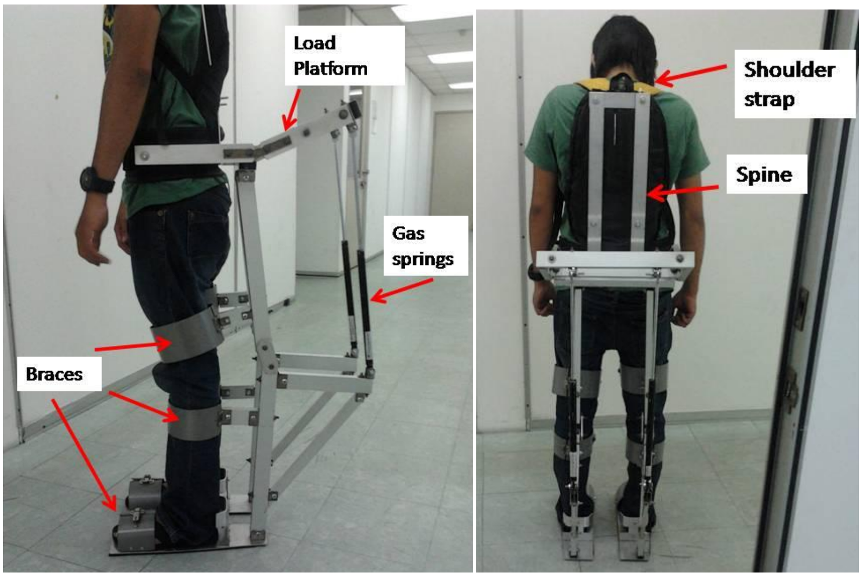


Fig. 2: The views of the exoskeleton concept system

A pressure sensor is placed on the underside of the shoulder strap, so that whenever a load is placed on the load platform, the pressure sensor would be able to provide the reading of the pressure applied to the *retral deltoid* or circa the shoulder blade. This reading is based on the amount of pressure placed due to the connection of the shoulder strap to the spine and load platform. The transmission is done internally within the exoskeleton itself, again to avoid tethering.

3. Experiment Setup:

A specific small set of stairs i.e. 5 steps are used in this experiment. The reason of this selection is twofold; the stairs is wide for security reason (in the event of the wearer lost out stability) and short range provides easier measurement (heartbeat, pain threshold level).

The subject (wearer) was required to climb up and down the 5 steps stairs while carrying a load using a typical traveler's backpack. This situation was the benchmark of the wearer's performance. The load and the backpack was constant (same type, size and weight) throughout this whole experiment, controlled by the pressure sensor placed in between the backpack shoulder strap and the subject's shoulder. This action was repeated 5 times and readings were recorded. Each action of ascending and descending the stairs is considered as 1 cycle. Each cycle are done consecutively. The measurements that were recorded are pressure applied on shoulder (to compare load transferred), the wearer's heartbeat rate (to understand the fatigue level of the wearer), and the time taken to reach the top of the flight (to compare normal motion versus exoskeleton aided motion).

The same reading method were recorded when the wearer was carrying the same load with the aid of an exoskeleton. Again, this action was repeated 5 times. For full optimization of the results obtained, a gap of 2 hours was given so the wearer would have sufficient rest and restores the energy level. Again, the positioning of measurement devices is similar to when the subject is not with the aid of an exoskeleton, as illustrated in Fig. 3.

Fig. 3: The measurement taken from the subject

RESULT AND DISCUSSION

To understand the extent of this exoskeleton system helps the wearer in term of handling the load, two set of measurements were recorded. These readings would indicate the feasibility of the subject handling load in the backpack using the exoskeleton. The feasibility in this context covers two aspects; the load bearing assist and the motion of the subject.

Table 1: The subject's heartbeat reading while ascending and descending stairs

Data Reading		
Reading Set	Without Exoskeleton (bpm)	With Exoskeleton (bpm)
1	78	78
2	86	82
3	96	86
4	99	90
5	107	94

In load bearing assist, measurement of assist provided by the exoskeleton is calculated through the difference of the heartbeat of the subject, comparing the beats per minute (BPM) when the subject is handling the load with and without the aid of exoskeleton. This difference between the values would indicate the difference in term of the subject's fatigue, as a delayed result for the subject to achieve peak bpm would be an indicator of this. The readings are as indicated in Table 1. Each reading set represent the subject ascends and descend the stairs in one cycle. The baseline reading was tare for both situations (with and without exoskeleton).

The null hypothesis for this condition is that the value of heart beat rate would be the same for both conditions. An independent-samples t-test was conducted to compare this heart beat rate in between two conditions; when the subject is not wearing exoskeleton and when the subject is aided by the exoskeleton. There was a significant difference in the scores for when the subject is not wearing the exoskeleton (M=93.2, SD=11.34) and when the subject is aided by the exoskeleton (M=86, SD=6.32) conditions; t(4)=3.1158, p=0.0178. These results suggest that wearing exoskeleton have an effect in the subject's fatigue. Specifically, this results suggest that when the subject is wearing exoskeleton, the peak value is delayed.

In human motion in term of climbing a set of stairs, the activation of muscles, primarily those of lower extremities, is in synchronization with each other. This situation comes in natural and is performed semi-involuntary by the human body, assisted by the input from senses, signals from the brain process and balancing by the upper extremity of the human body, similar to those of walking. This motion, by comparison, is closely similar to every person, barring the variables of the anthropometry of the human (i.e. limb's length, energy level, fatigue level etc.).

Due to this, a particular design of an exoskeleton must consider the freedom of this motion, since the motion of a subject wearing an exoskeleton will limit the natural motion of the subject to a certain degree, subjected to the articulation, number of degree of freedom and range of motion allowed by the exoskeleton. These variables is highly regarded in the design of this particular exoskeleton to minimize any limitation towards the motion of the subject through comparison of standard Malaysian male students size aged ranging from 18 to 24 years old (Karmegam, K. *et al.*, 2011). However, due to the attachments of foreign limbs of the exoskeleton to the limbs of the subject, some level of limitation is still present, and this minimized limitation is the theme of discussion in this experiment.

Similar to the previous experimentation, the benchmark was set with the subject handling the load without the assist of the exoskeleton. The subject then ascends and descends the stairs using the same load with the assist of the exoskeleton, and the time taken for the subject to complete each cycle were recorded and compared. The time taking technique used here is the video strip technique, where set of alternating colored strips was in line with the motion of the subject and the stairs, creating clear visuals of exact timing down to each seconds through video playback. Comparisons are further translated as indicated in Table 2.

Table 2: Time taken for the subject to complete each cycle

Data Reading		
Reading Set	Without Exoskeleton (Seconds)	With Exoskeleton (Seconds)
1	10	20
2	12	23
3	16	24
4	17	24
5	20	28

It can be seen that the time taken for the subject to complete a cycle is longer during load handling with the aid of exoskeleton compared to when the subject is working alone. The null hypothesis for this condition is that the time taken would be the same for both conditions. An independent-samples t-test was conducted to compare the time taken in between two conditions; when the subject is not wearing exoskeleton and when the subject is aided by the exoskeleton while ascending and descending the stairs. There was a significant difference in the scores for when the subject is not wearing the exoskeleton (M=15, SD=4) and when the subject is aided by the exoskeleton (M=23.8, SD=2.8635) conditions; t(4)=-11.9744, p=0.000279. For this result, the negative value was dropped due to the fact that time taken is longer when the subject is wearing the exoskeleton. These results suggest that wearing exoskeleton have an effect in the subject's motion. Specifically, this results suggest that when the subject is wearing exoskeleton, the time taken to complete the sets are longer.

However this delay can be accepted should the subject is not required to work against the clock.

A comfort scale test score was pre-assigned in order to determine the threshold of the subject's comfort level when operating the exoskeleton to performed the assigned task. The comfort level of the subject was assessed based on these score by two observers to obtain a third person viewpoint. This comfort level score is significant in the exoskeleton design, as a low level of comfort score would affect the performance of the subject when performing the task assigned. The acore assigned and average of scores was taken based on these two observers; and the result as in table 3 and table 4 respectively.

Table 3: Comfort Score Scale

Data Reading				
Respiratory	Physical movement	Facial Expression	Concentration	Score
No apparent coughing	Moving freely, normal ROM achieved	Relaxed	Normal response, able to response to observer	4
Mild visible breathing, no coughing	Smooth motion, occasional side stepping in climbing stairs	Normal, occasional expression	Normal response, occasional lapse in responding	3
Heavy visible breathing, coughing	Awkward motion, side stepping to ascend stairs	Tension in facial muscles	High concentration on moving, slow response to observer	2
Heavy breathing with visible motion of thorax muscles	Drag while walking, unable to achieve ROM	Grimacing of facial muscles	High concentration on each steps, ignorance of surrounding	1

Table 4: The subject's score

Data Reading		
Observer 1	Observer 2	Average points
3	4	3.5
3	3	3
2	4	3
2	2	2
	TOTAL (Average by 4)	2.875

Based on the total score, the upper middle average value of 2.875 out of 4 indicates the level of comfort (71.875%) and this point was set as the benchmark for further test on this exoskeleton design. The same scale will be preserved for future references while the grand total is set as threshold for this particular subject.

Conclusion:

Under this partial experimentation with exoskeleton in term of handling loads, it was conferred that any means of mechanical system (powered or non-powered) may provide the extra assist to the subject, where it have the capability in delaying the subject's fatigue level. However, this edge causes the delay of the subject during motion, in this particular case, ascending and descending stairs. The purpose of this study is to find the viability of using exoskeleton as mentioned. It was suggested that the exoskeleton would significantly assist the subject by delaying fatigue, and this was proven in the test conducted, where there is a significance difference in between the two conditions with a p value of 0.0178 from a preset significance level of 0.05, where the subject peaked earlier when unassisted gave the t value of 3.1158. This however was drawn back by the time taken to complete the same cycle, with a significance difference in the time taken to complete 5 cycles with a p value of 0.000279, where the difference is significance of a t value of 11.9744. These results suggest that the aid of exoskeleton is feasible in term of augmenting the subject's capability in handling load but this advantage is compensated by the subject's reduced motion speed.

Hence, it can be concluded that, shall the subject is allowed to expand time during operation, the exoskeleton usage in handling materials and assisting during payload bearing can be deemed feasible. Further assist and higher payload capability shall be achieved with a powered exoskeleton system with pneumatic actuators, as intended in the Shadow-Suit exoskeleton concept design, adding to its practicality and feasibility level of utilizing exoskeletons in material handling.

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