IGM Exchange Report

Research Title

Evaluation of spring implementation to reduce the required motor power in a walking assist exoskeleton with linear actuators (Walking Assist Machine using Crutches)

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General	
Accommodation	Umegaoka Dormitory
Living Costs	± €1400 / month (incl. travelling)
Scholarship	€700 / month
Flight Tickets	€800 (both ways)
Scholarship flight tickets	€1000
Language	10*1.5h language course in The Netherlands 25*1.5h language course at Tokyo Institute of Technology
Cultural aspects	It was a great experience to live in Japan, the Japanese people were really nice and very helpful to me. Social live with the laboratory members was very important and valuable to me. I met a lot of interesting people, Japanese and International.
Difficulties	I didn't experience any big difficulties.
Suggestions	Although most people at Tokyo Institute of Technology can speak English pretty well, learning some basic Japanese makes the experience even more interesting.

Evaluation of spring implementation to reduce the required motor power in a walking assist exoskeleton with linear actuators (Walking Assist Machine using Crutches)

A.F. Lafeber

***Abstract*—Powered robotic exoskeletons used to assist in human locomotion require a lot of energy. The Walking Assist Machine Using Crutches (WAMC) is such an exoskeleton used to assist paraplegic people in walking. It uses telescopic links driven by linear actuators with electro motors and people wearing the device move crutches themselves. An evaluation was done to see if the implementation of springs could lead to a reduction in required motor energy. A computer simulation calculating the movement of such a configuration with springs indeed showed a reduction in required motor energy and also effected in a higher walking speed. The user had to spend more effort to swing the crutches.**

***Index Terms*—Spinal Cord Injury, Crutches, Exoskeleton, Parallel spring, Walking Assist**

I. INTRODUCTION

MANY people suffer from Spinal Cord Injury (SCI) induced paralysis. For example, in the United States the number of people who have a SCI in 2010 has been estimated to be approximately 265,000 persons [1]. Of the people with SCI in the National SCI Database of the United States, 44% is paraplegic and 56% is tetraplegic [1]. This means that approximately 116,000 people are paraplegic, they have paralyzed lower limbs but functional upper limbs.

Paraplegic people usually have a wheelchair. When their upper body is functioning sufficiently, they can successfully move themselves with a wheelchair. However, there are some environments which are not accessible by wheelchairs, such as narrow passages, rough surfaces and stairs. To provide paraplegic people mobility in such difficult environments various powered robotic exoskeletons which assist in human locomotion are currently in development. One of them is the Walking Assist Machine using Crutches (WAMC) [2]. Also the goal of this machine is to function as a replacement for wheelchairs, for instance making it possible to ascend and descend stairs [3].

A disadvantage of powered robotic exoskeletons currently in development is the high amount of energy needed to drive them. While wheelchairs only have to overcome friction while driving at constant speed, exoskeletons have to repeatedly accelerate and decelerate the segments and have to provide dynamical support against gravity. For example, the power consumption of the WAMC was estimated to be 65 W at a slow walking speed of 0.44 m/s.

Because of this high energy consumption, solutions to save energy needed for walking with the WAMC were thought up. A method to store energy in a spring and release the energy at the right moment was developed. The energy efficiency and the effects on the kinetics and kinematics were analyzed. This was done by simulating the motion of a model of the WAMC in which the spring was implemented.

Functioning and composition of the WAMC

The WAMC is an electrically powered robotic exoskeleton which assists paraplegic people in walking. It is currently under development at Tokyo Institute of Technology. It is meant for people who cannot move their lower extremities voluntarily but who have a fully functional upper body. The level of actuation is controlled by a PD controller using a reference motion. This reference motion is based on the motion of a healthy person walking only with crutches. Users of the WAMC can operate the crutches in the same way as the healthy persons. The motion of the feet relative to the hip is then accomplished by a telescopic link driven by a linear actuator.

The composition of the WAMC can be seen in Fig. 1. The WAMC has a footplate on which the feet are strapped up. On the footplate two long links are connected by spherical joints. These links are both called “lower link” and consist of a pipe and a rack. Both the “upper links” are connected to the racks of the lower links by a rack and pinion system, such that the upper links can move up and down in the same direction as the lower links. This motion is driven by two DC motors. These motors are mounted on the upper links and are connected to gear reduction sets which are also mounted on the upper links. The gear reduction sets are connected to the rack and pinion systems. The combination of a DC motor, belt, gear reduction set and rack and pinion system is called the “linear actuator” and the combination of a lower link and upper link is called the

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“telescopic link”.

The weight of the user is transferred to the links by a waist band which is fixed to the upper part of the links. The connection of the feet with the footplate is purely meant to have a rigid connection with the feet and lower part of the link, not to transfer weight. The WAMC has force and position sensors to detect user intention and the current state of the system.

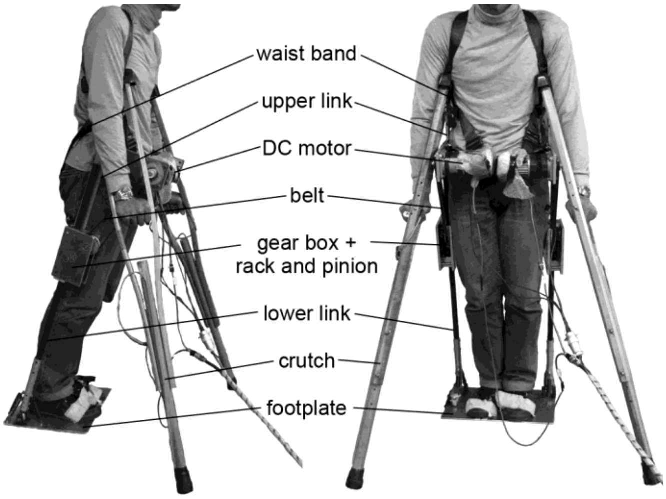

Fig. 1. Photograph of the WAMC wore by a user to show to composition of the different elements. The combination of a DC motor, belt, gear reduction set and rack and pinion system is called “linear actuator” and the combination of a lower link and upper link is called “telescopic link”.

II. METHODS

A rigid multibody model was made to describe the behavior of the machine. The effectiveness of the adjustment to save energy was evaluated using a computer simulation in MATLAB.

Model

The WAMC was modeled as a simple dynamic rigid multibody system acting in the sagittal plane with three degrees of freedom. A schematic drawing of this model can been seen in Fig. 2. Because of symmetry the two crutches were seen as one crutch and also the two telescopic links were seen as one telescopic link. Three generalized coordinates were used: the angle of the crutch q_1, the angle of the telescopic link q_2 and the extension of the telescopic link q_3. Together with their derivates to time the state of the system consisting of three bodies was fully described.

Furthermore the following parameters were used: Length of the crutch L_{crutch} = 1.37 m, length of the telescopic link $L_{\text{tlink}} = L_{\text{lower}} + q_3 + L_{\text{upper}} = 1.12 + q_3 + 0.50$ m; masses were modeled as m_{crutch} = 8 kg, m_{upper} = 60 kg and m_{lower} = 15 kg and moments of inertia around the centers of mass of the crutch, the upper link and the lower link were respectively I_{crutch} = 1.23 kg m, I_{upper} = 1.53kg m, and I_{lower} = 1.12 kg m. The center of mass of the crutch was at $0.63L_{\text{crutch}}$ from the right hinge at the ground, of the upper link at $0.33L_{\text{lower}}$ from the upper hinge and of the lower link at L_{lower} from the left hinge on the ground.

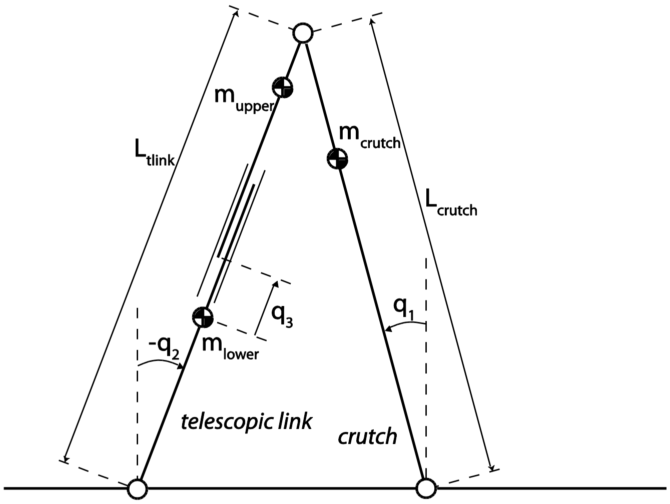

Fig. 2. The model of the WAMC which was used for the dynamic simulation. It consists of 3 bodies; a crutch, an upper link and a lower link with their masses. The system has three degrees of freedom described by the generalized coordinates q_1, q_2 and q_3.

Two external loads were described. The force which acts at q_3 delivered by the linear actuator and the torque between the crutch and the telescopic link, both variant in time. The (relatively low) torque between the crutch and the telescopic link can be supplied by the user by moving the arms relative to the upper body in the sagittal plane.

The motion of the model was obtained by calculating the values of $\begin{bmatrix}\vec{q}\\ \dot{\vec{q}}\end{bmatrix}_n$ at each time sample n by numerical integration using the Runge Kutta 4th order method [5] with a sample time of 0.005 s. Initial conditions were $q_{1,0}$ = 0.365 rad, $q_{2,0}$ = -0.125 rad and $q_{3,0}$ = 0.270 m.

Accelerations of the generalized coordinates needed for the numerical integration were calculated using the TMT-method [4] with a manually adjusted transformation matrix:

$$\begin{bmatrix}\dot{\vec{q}}(t)\\ \ddot{\vec{q}}(t)\end{bmatrix} = f\left(\begin{bmatrix}\vec{q}(t)\\ \dot{\vec{q}}(t)\end{bmatrix}, \vec{F}_{input}(t)\right) \tag{1}$$

In which $\vec{F}_{input}$ contains the force from the linear actuator at the rack and the torque between the link and the crutch supplied by the user.

One step consisted out of three phases which all required their own equations of motion. The simulation thus consisted out of three sub simulations for consecutively phase A, phase B and phase C. These phases are illustrated in Fig. 3. and can be defined as follows:

- Phase A: the “push-off” phase. The linear actuator drives the telescopic link such that q_3 increases. The angles q_2 and q_1 decrease until q_1 is close to 0 rad, the walker almost “falls over”.
- Phase B: the “link swing” phase. The linear actuator drives the telescopic link such that q_3 decreases again. The

endpoint of the link loses contact with the ground and swings forward until it touches the ground. The crutch acts as a stance leg.

- Phase C: the "crutch swing" phase. After impact, which is modeled using the conservation of impact law, the linear actuator delivers force to carry the weight of the system and the crutch swings forward until it touches the ground.

When the crutch hits the ground one complete step is finished. All generalized coordinates are the same again as in the beginning of the step such that a new step could be done. Also the state of the system is thus the same again. The only difference is the translation of the model as a whole. For example the endpoint of the crutch has now moved to the right on the ground with one step length of 1.17 m. One complete step had a duration of 2.7 seconds. This results in a walking speed of 0.44 m/s (1.6 km/h).

For phase A and phase B the lowest point of the crutch was chosen as a start point to describe the vector containing the locations of the centers of mass. For phase C the lowest point of the telescopic link was chosen as a start point. For phase A a constraint was added to the equations of motion to make it a four link closed loop model. The constraint stated that the lowest point of the telescopic link should keep its position on the ground. Phase B and C were modeled as a three link open loop model.

To verify the calculated motion and to help understanding of the outcome and tuning of the input forces the calculated motion was visualized by an animation with the state of the model plotted in time.

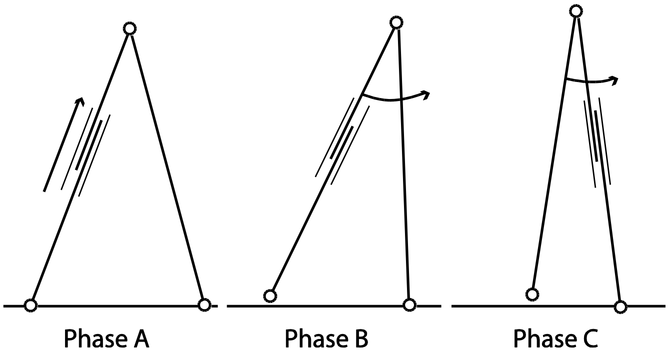

Fig. 3. The three phases of one step: phase A, "push-off"; phase B, "link swing" and phase C, "crutch swing".

Goal

The simulation of the model without the adjustment showed that the electrical energy for one step which should be provided by the DC motors was 173 Joule. 40% of this amount during phase A, 24% during phase B and 36% during phase C. These higher amount during phase A and C can be explained considering the actions at all phases. As can be seen in Fig. 3, during phase A and C the actuator has to support (part of) the weight of the system by providing a force to push the upper and lower link from each other. This is different from phase B, where the actuator only has to overcome the gravity force of the lower link. Considering these energy accounts, the goal was to design a method to save energy during the "push motion" during phase A and C.

Possible working principles

The motors have to provide a lot of energy to lift the weight during phase A and C. At the end of phase B a lot of energy is lost when the link hits the ground. It seems beneficial to store this energy in order to use it to lift the weight. This could for example be done by elastic elements or hydraulic systems. The simplest way to accomplish this would be elastic elements such as springs or rubber bands. They are cheap and do not need much space or maintenance.

Various working principles could be thought of, as can be seen in Fig. 4. The three main types are: a) a compression spring in series in the lower link, b) a tension spring parallel to the movement of the lower and upper link relative to each other and c) making the actuation element elastic for example by making the bands driving the linear actuator elastic.

The series and parallel spring seem feasible to implement on the real model considering the geometry of the real exoskeleton. The elastic actuation will be too complex to implement in this case because the gear reduction is not situated at the motor shaft but at the linear actuator, the speed of the belt will then be way too high.

A compression spring in series will help to reduce the peak power which is encountered when the telescopic link hits the ground after a swing, because it will make the change in velocity more fluent. However, this will only shortly have a significant effect. It would be more effective to constantly have a reduced force which has to be delivered by the motor because the weight has to be compensated constantly. For this reason the parallel spring working principle was chosen.

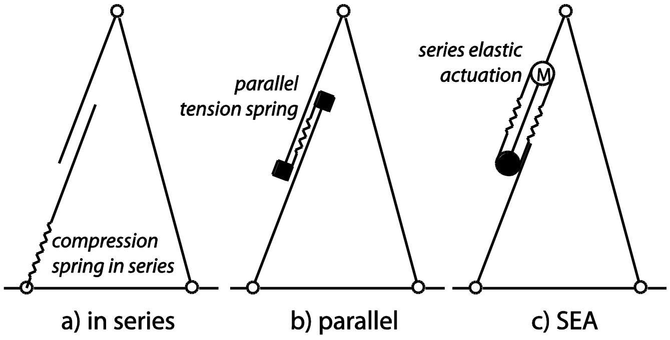

Fig. 4. Possible working principles as a method to save energy: a compression spring in series, a parallel tension spring or series elastic actuation.

Design of the parallel spring mechanism

Using a parallel spring in the same configuration as in Fig. 4b brings in one problem which had to be solved. During phase A the spring releases its energy which is very beneficial, but during phase B the spring is a major hindrance. In order to achieve foot clearance such that the footplate does not hit the ground q_3 has to decrease again. The motor has to work actively into the direction of the spring again which costs a lot of energy.

A configuration with an angle dependent spring tension was chosen to solve the problem. The cable which is connected to the spring was routed from the telescopic link to the crutch in order to vary the length of the cable with the angle between the telescopic link and the crutch. In this way the effect of the spring could be reduced during foot clearance. A schematic drawing of the configuration of this new system can be seen in fig. 5.

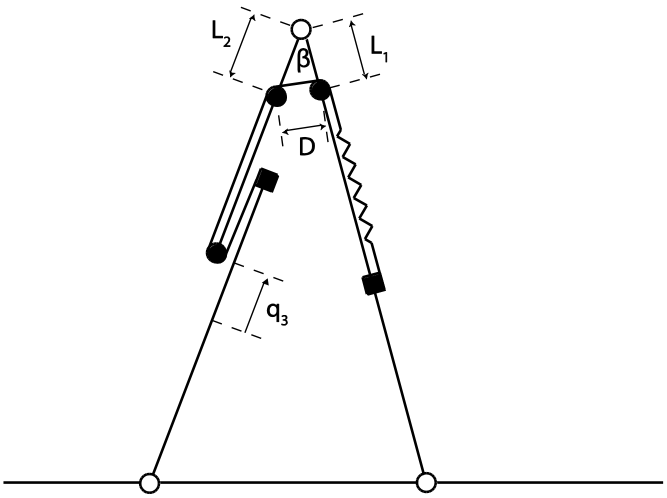

Fig. 5. Schematic drawing of the final configuration with the spring implemented. The parallel spring provides force during phase A while it does not hinder foot clearance during phase B because of the angle dependent distance D.

Parameter design

To analyze the concept of the parallel spring a linear spring was chosen as elastic element. The properties of this spring were chosen with the following criterion in mind: "The elastic element should at all time provide the amount of force as close to the desired amount of force at that time during phase A". To evaluate this amount of force, the force between the upper and lower link was plotted against the theoretical enlargement of the spring, as can been seen in Fig. 6. The theoretical enlargement was defined as follows:

$$D_{spring} = q_{3,0} - q_3 + D_{spring,\max} + D(\beta) - \max(D(\beta)) \quad (2)$$

In which $q_{3,0}$ = 0.27 m is the initial value of q_3, $D_{spring,\max}$ = 0.15 m is the maximal desired extension of the spring, $D(\beta)$ is the length of the cable between the link and crutch, dependent on the angle between the link and the crutch β and max($D(\beta)$) is the maximum value of this length.

The maximal extension of the spring was chosen as 0.15 m because it is geometrically desirable. With this maximal extension the stiffness could be determined. This was first done for the simple parallel spring system without a cable routed between the link and the crutch. In this case $D(\beta)$ is always 0. The graph of the force versus the spring enlargement for this case consists of three main lines as can be seen in Fig. 6. The upper line shows the extension during phase B with a force which is almost constant. The lower line shows the extension during phase C with a force which is also almost constant but not as large because the weight is not carried by the telescopic link in this case. The middle line shows the force versus the extension during the push-off phase. The elastic element was expected to be most effective when its force-extension properties will fit the middle line as good as possible. A straight line was drawn representing this spring properties. The line was drawn between the point of zero force and extension and the point of maximal force and extension with the slope of the line representing the spring stiffness. The theoretical force delivered by the spring was below the desired amount all the time, especially when the extension was getting smaller. The stiffness of the spring was chosen a bit larger such that is provides a little more force in the beginning of the push-off and a less force during the end of the push-off. The spring stiffness k_{spring} was chosen as 700 N / 0.15 m = 4.7 kN/m.

For the system with the spring cable routed to the crutch the distance L_1 and L_2 (which can been seen in Fig. 5) were chosen by the following criterion: "the range of $D(\beta)$ should be such high that there is no spring tension during theoretical maximal foot clearance when β = 0 and the distance between the ground and the soleplate is 4.0 cm, where L_1 and L_2 should be optimized to induce the minimum amount of torque between the link and crutch". This resulted in L_1 = 0.38 m and L_2 = 0.42 m. As can been seen in Fig. 6, the desired force during phase A has changed almost nothing, so there was no need to adjust the spring stiffness k.

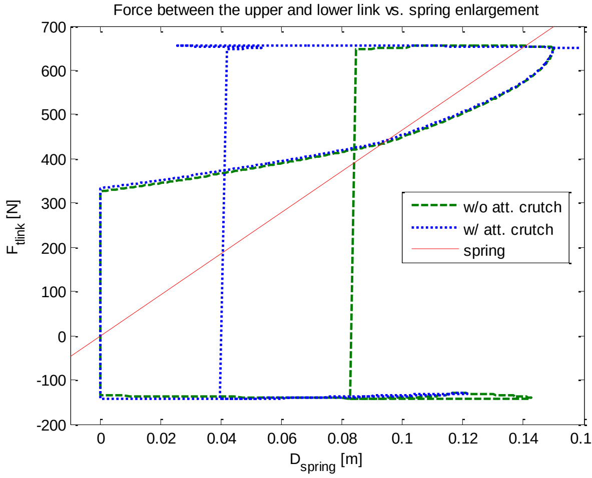

Fig. 6. Force between the upper and lower link vs. theoretical spring enlargement. On this graph (w/o att. crutch) a straight line was fitted with its slope representing the ideal spring stiffness. In case of the spring cable routed to the crutch (w/ att. crutch) it can be seen that there is no need to change to the spring stiffness. It was chosen as k = 4.7 kN/m.

Control method

To reproduce the same motion with the spring implemented, calculating the required input force was not possible by an inverse dynamic analysis such as done by A.J. van den Bogert [6], since the system has three degrees of freedom and only q_3

could be adjusted by the linear actuator and the angle between the link and crutch could be adjusted a little bit by the user. However first analysis using the simulation showed that the motion of the system without a spring could be reproduced well using a PD controller with only the values of q_3 and $\dot{q}_3$ as reference. This suggested that it will also be possible to control the system with a spring attached with a PD controller using only q_3 and $\dot{q}_3$ as a reference.

The usefulness of the existing motion from the system without a spring as a reference signal for the system with a spring was judged. From the simulation it turned out that it was much more effective to use a different reference pattern, manually adjusted for the new system.

Test users of the prototype of the WAMC told that the speed of push-off at the beginning influences the feeling of safety. A push-off speed $\dot{q}_3$ which is too high makes the forced motion a bit frightening. For this reason the reference motion at phase A was kept almost the same. A PD controller with the motion of q_3 and $\dot{q}_3$ from the system without the spring as a reference was used to calculate input force for phase A. Reference force patterns for phase B and C with the spring were both created different to obtain a realistic motion during these phases. Tuning these reference forces was done partly by watching the effect of a changed force pattern on the motion in the animation and by calculating desired forces with a PD controller with a desired motion as reference.

Evaluation

To analyze the effectiveness of the solution, the required power and energy with and without the spring attached were compared. Also the feasibility of the input forces by the linear actuator and by the user were analyzed.

III. RESULTS

Input force, power and energy

In Fig. 7 the required input force with and without the spring is shown and in Fig. 8 the required motor power and electrical energy with and without the spring are shown. Also the phase changes of the system with spring are indicated by the vertical lines and phase letters. Required energy levels for every phase are shown in Table 1. As expected, the motor has to deliver a lower force during phase A which results in a lower required power consumption saving 42% of the required energy. First the power consumption in phase B is similar. Phase B of the system without a spring lasts longer but doesn't need much power then. Finally the energy consumption of the system with spring during phase B is 97% of the energy consumption of the system without a spring during phase B. During phase C a higher power is required but thanks to the shorter swing time of the crutch 60% of the energy can be saved during this phase. The total energy needed for one step was 108 Joule instead of 173 Joule, a total energy saving of 37%. The average motor power decreased with 12 %, from 65 W to 57 W.

Although the motor has to deliver less energy, the user has to exert a continuous torque of 20 Nm on the crutches in the sagittal plane, resulting in a higher required physical effort of the user.

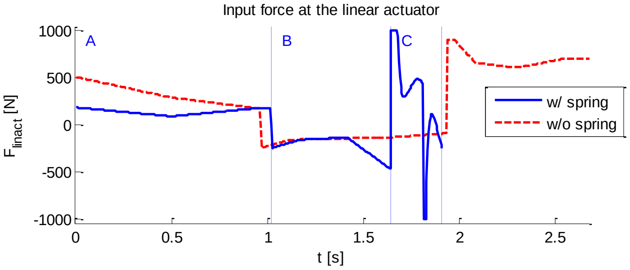

Fig. 7. Input force at the linear actuator.

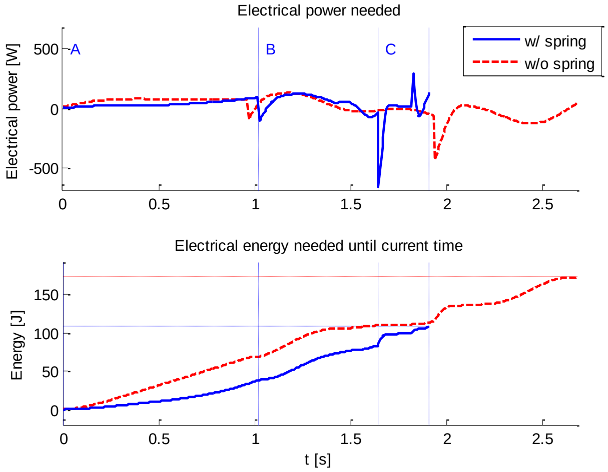

Fig. 8. Electrical power and energy needed.

TABLE 1

ENERGY REQUIREMENTS

Phase	Motor energy needed w/o spring	Motor energy needed w/ spring
A	66.7 J	38.7 J (58%)
B	48.0 J	46.6 J (97%)
C	58.0 J	23.0 J (40%)
Total	173 J	108 J (63%)

Energy needed from the motor at each phase in a step and total energy needed in one step, with and without the implementation of the spring.

Duration

A plot of the generalized coordinates versus time of the system with and without spring can be seen in Fig. 9. Durations of all walking phases can be seen in Table 2. Phases A lasted 6% longer and phase B and C were respectively 35% and 64% shorter.

With the same push-off characteristics, the walking speed increased. The system without the spring needed 2.67

seconds to perform one complete step of 1.17 m, resulting in a walking speed of 0.44 m/s (1.6 km/h). The step time of the system with the spring is reduced to 1.91 seconds, for almost the same step length, 1.16 m. This results in a walking speed of 0.61 m/s (2.2 km/h). The walking speed thus increased with 39%.

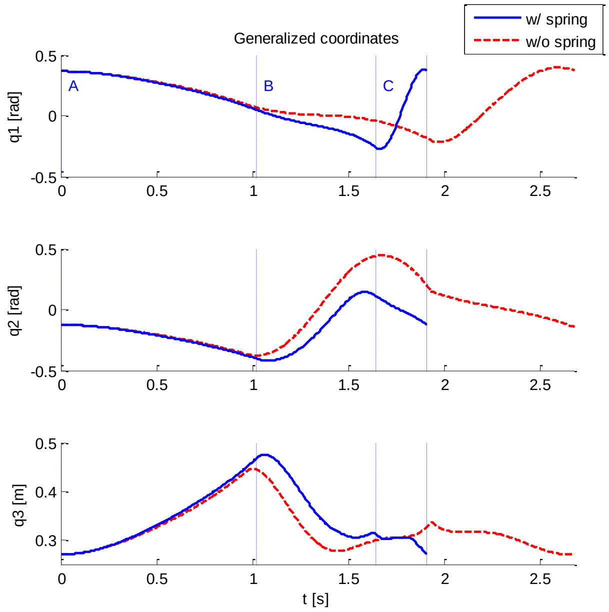

Fig. 9. Graph of the generalized coordinates showing the motion of the system with and without the spring in time.

TABLE 2
PHASE DURATIONS

Phase	Phase duration w/o spring	Phase duration w/ spring
A	0.97 s	1.02 s (106 %)
B	0.96 s	0.62 s (65 %)
C	0.75 s	0.27 s (36 %)
Total	2.68 s	1.91 s (71%)

Durations of each phase in a step and total duration of one step, with and without the implementation of the spring.

IV. DISCUSSION

The results of this study are promising. It was possible to reduce the energy which should be delivered by the motors. A theoretical energy saving of 37 % makes the system much more energy efficient. Also, as a side effect of the parallel spring which was routed with a cable from the link to the crutch, a torque was introduced between the crutch and the link. This made it possible to have shorter durations of phase B and C and increase walking speed. During phase B this was because the telescopic link could start rotating faster because of the induced torque by the spring and when the telescopic link passed the crutches, the rotational speed was decreased again by the induced torque by the spring. The rotational speed of the telescopic link now didn't have to be decreased by gravity only such as with the system without the spring. In other words, the user could "lean" forward further supported by the induced torque. Like for phase B, using similar reasoning also phase C was shorter.

Both simulations, with and without the spring, were performed from manually tuned reference motions and forces which were not equal for both systems. For this reason other results could be achieved with different reference motions and forces. However it can be said that the adjustment seems to greatly improve the efficiency.

A disadvantage of the current configuration is the effort it takes for the user to swing the crutches. The 2D model showed that a continuous torque of 20 Nm has to be exerted during the swing phase of the crutches to move them forward. Also further analysis in 3D space revealed an extra torque which has to be exerted by the user. When analyzing the 3D orientation of the system it can be seen that the crutches are not completely orientated vertically in the coronal plane, the crutches are pointing sideways. This means that when the springs are in tension not only a torque between the links and the crutches in the sagittal plane is induced but also a torque pulling the crutches to the vertical orientation in the coronal plane. This means that during the swing phase of the crutches the user has to actively push the crutches to the sides by exerting a torque to the crutches in the coronal plane. When the initial angle of the crutches to the sides is such that the end of the crutches are placed 0.40 m from the rotation point at the shoulders to the sides in the transverse plane, this torque is estimated to be: 63 Nm at the beginning of the swing of the crutches, reducing to 0 and then increasing to 138 Nm just before the crutches will hit the ground. This torque is very high. It is desirable to optimize the exoskeleton further to make these torque requirements lower. To reduce the required torque in the coronal plane it would be an option to decrease the angle of the crutches with the vertical in the coronal plane at the cost of stability or to use an extra elastic element to compensate for this induced torque.

The model could be made more realistic by determining the account of intrinsic friction, stiffness and damping at all four joints and adding the forces caused by these effects to the equations of motion. Although this might have the effect of generally slightly higher required input forces to overcome these effects, these effects are probably especially beneficial since less motor energy is needed to react to sudden velocity changes during impact when the telescopic link hits the ground. The great power peak of 659 W, which can be seen at that impact point, would be much lower then.

To further improve the efficiency of the exoskeleton some adjustments could be evaluated:

- Both a parallel spring and a spring in series could be used as a pair: The parallel spring seems to be able to reduce the force required from the motor. However there still is a large power peak when the telescopic link hits the ground. To reduce this peak a series spring could be used. The combination of these effects could be analyzed. Although there is suddenly a large force needed when the telescopic link hits the ground, it should be realized that this force will be a bit less in reality because some force will be delivered by intrinsic friction, stiffness and damping which is not modeled.

- The theoretical spring enlargement during phase B does not reach 0 as modeled but 0.025 m, as can be seen in Fig. 6. This is because the distance to the floor is more when β is exactly 0. The motion could be further optimized such that there is no spring tension at all during foot clearance at β = 0.
- The force – enlargement curve does not seem to be completely linear as can be seen in Fig. 6. Rubber bands instead of springs could maybe fit this curve better, since they provide a force relative to the enlargement to the power of approximately 2. The efficiency during this phase but also the effects on the efficiency during the other phases could be analyzed.
- Some alternative configurations could also be analyzed. For example a decouple mechanism or a double parallel spring. A decouple mechanism could decouple a parallel spring at the start of phase B, such that it is no hindrance during foot clearance. At the end of phase B the spring should be coupled again to get in tension again when the telescopic link moves towards the ground. This mechanism was not chosen because it might be hard to obtain completely safe operation. The state of the system is not only dependent of input forces but also of the decouple and couple actions. These actions could fail making the risk of falling high. A double parallel spring system could also help to relieve the system from problems with foot clearance. The crutches could be equipped with a spring system similar to the spring system of the telescopic link. The gravity force on the crutches could be transferred to the telescopic link by a Bowden cable with a gear ratio. This configuration was not chosen because it is very complex and requires a lot of components. Besides that it will probably be less effective because the two systems counteract each other.

V. CONCLUSION

As expected, the implementation of a parallel linear spring to the 2D model of the WAMC with the spring cable routed from the telescopic link to the crutch leaded to a more energy efficient system. The motor energy needed for one step of 1.17 m reduced from 173 to 108 J (63 %). The average motor power reduced from 65 W to 57 W (88 %). Furthermore, with the same push-off characteristics, the walking speed increased from 0.44 m/s to 0.62 m/s (141 %). The user has to spend more effort. With the adjustment the user now has to exert a torque on the crutches of 20 Nm in the sagittal plane during the swing phase of the crutches. Further analysis in 3D revealed an extra induced torque in the coronal plane, the maximum torque which should be compensated by the user at the end of the swing of the crutches is 138 Nm.

ACKNOWLEDGMENT

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