Does it pay to have a damper in a powered ankle prosthesis? A Power-Energy Perspective

Mahdy Eslamy[1,2], Martin Grimmer[1], Stephan Rinderknecht[2], Andre Seyfarth[1]

Abstract— **In this paper we investigated on peak power (PP) and energy (ER) requirements for different active ankle actuation concepts that can have both elasticity and damping characteristics. A lower PP or ER requirement is an important issue because it will lead to a smaller motor or battery. In addition to spring, these actuation concepts are assumed to have (passive) damper in series (series elastic-damper actuator SEDA) or parallel (parallel elastic-damper actuator PEDA) to the motor. For SEA (series elastic actuator), SEDA and PEDA, we calculated the required minimum motor PP and ER in different human gaits: normal level walking, ascending and descending the stairs. We found that for level walking and ascending the stairs, the SEA concept, and for descending, the SEDA, were the favorable concepts to reduce required minimum PP and ER in comparison to a DD (direct drive) concept. In SEDA concept, the minimum PP could be reduced to half of what SEA would require. Nevertheless, it was found that spring was always required, however damper showed 'task specific' advantages. As a result, if a simple design perspective is in mind, from PP-ER viewpoint, SEA could be the best compromise to be used for different above-mentioned gaits. For SEDA or PEDA concepts, a controllable damper should be used. In addition, our results show that it is beneficial to select spring stiffness in SEA, based on level walking gait. The PP and ER requirements would increase very slightly for stairs ascending, and to some extent (10.5%) for descending as a consequence of this selection. In contrast, stiffness selection based on stair ascending or descending, increases the PP requirements of level walking more noticeably (17-24%).**

I. INTRODUCTION

To mimic the musculoskeletal structure and mechanical function of human lower extremities in a powered (active) ankle prosthesis, various conceptual models of this complex biological system have been studied through different actuation schemes. They mainly consisted of motor and series, parallel or unidirectional parallel springs [1–7]. The main goals of these concepts are to decrease motor peak power (PP) and energy (ER) requirements and also the metabolic cost of transfer to provide stable human-like locomotion. In all those concepts, spring is a key part in the actuation mechanisms. The stored energy in spring during stance phase is released until push-off resulting in the decrease of PP-ER requirements of the active ankle prosthesis. A majority of focus has been devoted to level ground locomotion.

In addition to level walking, everyday life involves additional activities such as going up or down uneven or sloped surfaces [8] (e.g. stairs, hills). In [9] it was found that only little signs could be found that indicate an adaptation or shift in the locomotor patterns when moving from level to stair walking. Stair locomotion, being a common functional activity of daily living, has been used in the rehabilitation of the lower extremity as a motor performance test [10, 11] to increase muscle strength and weight-bearing capabilities of the joints. Furthermore, human muscular structure not only shows elasticity but also damping characteristics [12–14]. Recently in a patent, damper was embedded in a powered ankle prosthesis for absorbing impact energies [15]. For passive ankle prostheses (mostly for adaptation to sloped surfaces and not necessarily stair ascent-descent), the damper was used by Mauch in 70's in which prosthetic ankle could adapt to the ground slope [16]. Endolite Echelon foot-ankle is a commercially available passive hydraulic prosthesis [17]. In a recent study, a semi-active damper was added to a passive ankle prosthesis for negotiating on sloped surfaces to maintain stable contact and decrease the probability of falling [18].

The analysis of biomechanical (biological) and mechanical aspects (power-energy requirements) involved in level walking, stair ascent and descent together with investigation on the effect of damper and spring, can advance the development and design of powered ankle prostheses. The effect of spring for reducing PP and ER requirements in powered ankle prostheses is covered in literature [1–7]. A lower PP or ER requirement is an important issue because it will lead to a smaller motor or battery.

In this paper we investigate whether or not (passive) damper may reduce motor PP-ER requirements in a powered ankle prosthesis. The damper could be either in series or parallel to motor. To do this, we introduce two active actuation concepts other than SEA (series elastic actuator). The SEA was studied in literature [1, 2, 6, 7] which provides a basis for comparison. We calculate the PP and ER requirements of series elastic-damper actuator (SEDA), parallel elastic-damper actuator (PEDA) and SEA for normal level walking, ascending and descending the stairs (for each concept and for each type of locomotion). The SEDA could be considered as an extension of SEA concept. The PEDA concept is based on the conceptual Hill-type [12] muscle model that was used in [13]. Then, we compare PP and ER of these concepts to identify the concept that requires the minimum PP-ER for each gait. In addition, for an SEA concept, we investigate whether it is good to select the spring stiffness based on level walking or stairs ascending or descending, for minimum PP-ER requirements in an active ankle prosthesis.

[1]Lauflabor Locomotion Laboratory, Technical University of Darmstadt, 64289, Germany,

[2]Institute for Mechatronic Systems in Mechanical Engineering (IMS), Technical University of Darmstadt, 64287, Germany, email to: m.eslamy@gmail.com

978-1-4673-6024-1/13/$31.00 ©2013 IEEE

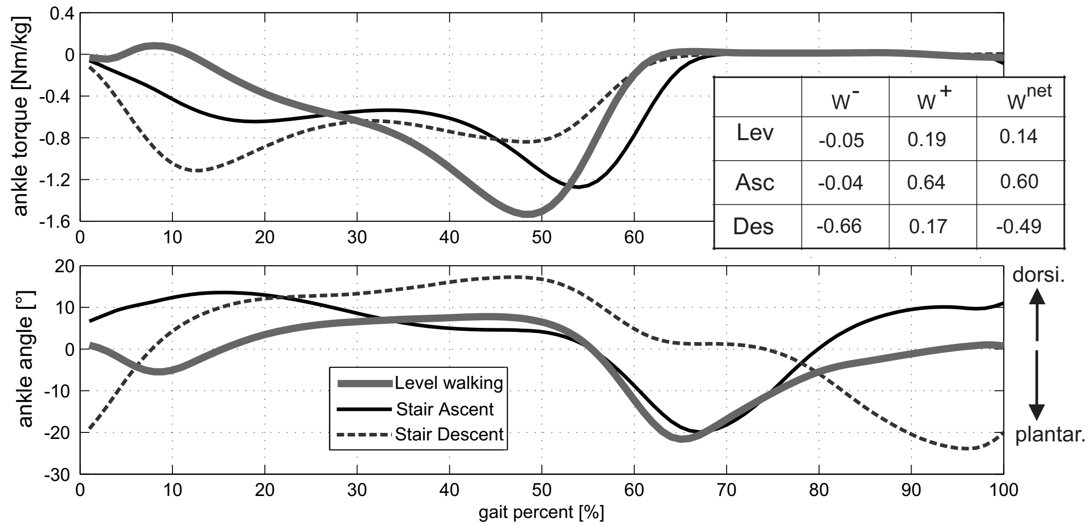

Fig. 1. Human ankle torque (T_{ank}) and angle for normal level walking (1.5m/s, [19]) and normal ascending-descending the stairs (slope 30°, [9]), with information for biological negative (W^-), positive (W^+) and net work (W^{net}, J/(kg.m)) in ankle joint.

TABLE I

MAIN FEATURES OF ANKLE KINEMATICS AND KINETICS FOR NORMAL LEVEL WALKING [19], NORMAL STAIRS ASCENT AND DESCENT [9]

Gait type	Max. Biological Power [W/kg]	Max. Torque [Nm/kg]	ROM (range of motion) (+ = dorsi. | - = plantar.) [°]	stance until [%]	Speed, slope [m/s], [°]	cycle time [sec]
Level walking	3.2	-1.53	+7,-21	65	1.5m/s	0.98
Stair Ascent	2.55	-1.27	+14,-20	68	0.48m/s (30°)	1.41
Stair Descent	-2.85	-1.11	+18,-24	65	0.57m/s (30°)	1.19

II. FUNDAMENTALS AND METHODS

The ankle kinematics and kinetics of able-bodied subjects during level walking, stairs ascending and descending were obtained from [9, 19]. The data correspond to healthy subjects with about the same height, body mass and age group. A comprehensive information on the procedure for experiments, data acquisition and analysis can be found in those references.

A. Human gait in level walking, stairs ascent and descent

Before designing a powered prosthetic ankle for daily activities, it is necessary to understand human locomotion in different conditions like level ground, ascending or descending the stairs. Human gait involves recurring patterns of foot (leg) movements, rotations, and torques. In Fig. 1, the ankle torque and ankle angle are shown in a gait cycle, together with information about negative, positive and net work of the ankle joint for the above-mentioned gaits. In addition, the main characteristics of human ankle biomechanics for those three gaits are shown in Tab. I. The ankle torque T_{ank} is normalized to body mass. The gait cycle starts with foot contact and ends with the next contact of the same foot. Note that the absolute value of ankle joint net work in ascent or descent is noticeably higher than level walking. In addition, there is one peak in ankle torque for level ground locomotion, however for stair ascent-descent there are two local peaks which are mainly due to weight acceptance and propulsion. The range of motion (ROM) increases from level walking to ascent and reaches the highest in stair descent. The ankle torque T_{ank} is converted to ankle force F_{ank} using lever arm and system geometry (Fig. 2a). The length x_g (Fig. 2) is calculated by using ankle angle [9, 19] and geometrical dimensions (see Fig. 2a, also [6, 7]).

B. Power requirements of SEA

For SEA (Fig. 2b), power calculation is discussed in [1]. Here, we briefly mention it and focus more on the other actuation concepts in this paper. The transmission type in powered ankles are mainly ball screw [1–3] and we also base the calculations on this type of mechanism. The required motor power P_m for SEA is [1]

$$P_m = F_{ank}(\dot{x}_g + \frac{\dot{F}_{ank}}{K_s}) \tag{1}$$

where K_s is the stiffness of the series spring.

C. Power requirements of the series elastic-damper actuator (SEDA)

Also mentioned in section I, the SEDA concept (Fig. 3) could be considered as an extension of SEA [1]. The required motor power P_m is obtained by the multiplication of motor Force F_m and ball screw nut velocity [20]. The ankle force, motor force or nut velocity in general could be positive (to the left) or negative (to the right, Fig. 3). Like [1] we assumed if T_{ank} is negative, F_{ank} is negative (T_{ank} is known, Fig. 1). In SEDA, F_{ank} and F_m have similar absolute values but different signs (Newton's third law). Therefore,

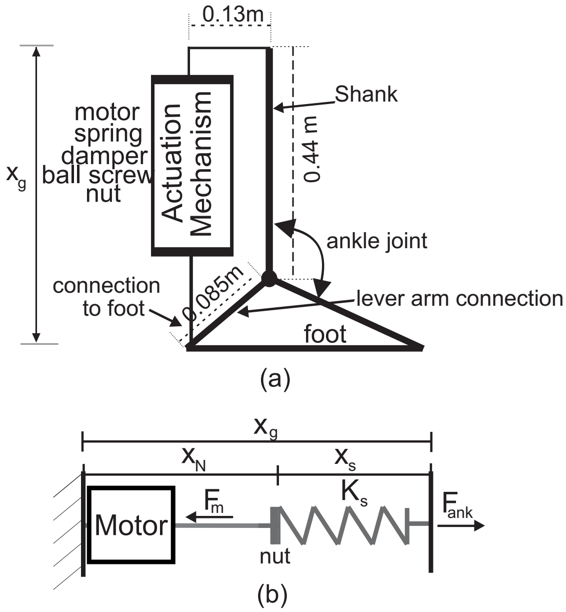

Fig. 2. Schematic view of (a) the powered ankle with dimensions used for calculations [6, 7] and (b) model of series elastic actuator SEA [1].

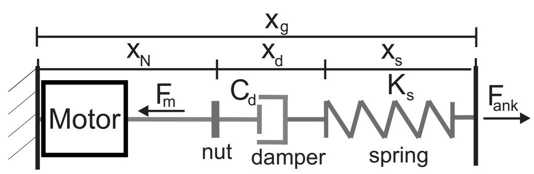

Fig. 3. Model of series elastic-damper actuator (SEDA).

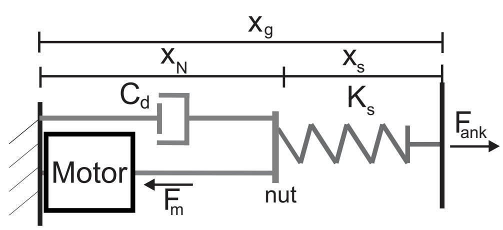

Fig. 4. Model of parallel elastic-damper actuator (PEDA).

we have shown them in different directions in Fig. 3. To be dynamically correct for the equations [20], as we took the left direction positive, the nut velocity could be represented by $\dot{x}_{_N}$ but with opposite sign, note $x_{_N}$ is a distance and when elongated, $\dot{x}_{_N}$ is naturally positive, but nut velocity would be negative according to the selected positive-negative directions. We chose this method to be similar to the method presented in [1]. Therefore

$$P_m = -F_m \ \dot{x}_{_N} \tag{2}$$

Using Fig. 3 the length x_g (see also Fig. 2) is obtained as

$$x_g = x_{_N} + x_d + x_s \tag{3}$$

For spring and damper we have

$$F_{ank} = -C_d \dot{x}_d \tag{4}$$

$$F_{ank} = K_s(d_{0s} - x_s) \tag{5}$$

where C_d is the damping coefficient, K_s is the series spring stiffness and d_{0s} is its free length. Using Eq. 3-5, for $\dot{x}_{_N}$ we have

$$\dot{x}_{_N} = \dot{x}_g + \frac{\dot{F}_{ank}}{K_s} + \frac{F_{ank}}{C_d} \tag{6}$$

based on Eq. 2 the required motor power P_m is calculated as

$$P_m = F_{ank} \ (\dot{x}_g + \frac{\dot{F}_{ank}}{K_s} + \frac{F_{ank}}{C_d}) \tag{7}$$

we discuss this further at the end of subsection D.

D. Power requirements of the parallel elastic-damper actuator (PEDA)

The PEDA concept (Fig. 4) is based on the conceptual Hill-type [12] muscle model that was used in [13]. Using Fig. 4 we write (Newton's second law, note F_{ank} is known, in Fig. 4 the direction of motor or ankle force are shown for an arbitrary moment)

$$F_m = -(F_{ank} + C_d \dot{x}_{_N}) \tag{8}$$

and

$$F_{ank} = K_s(d_{0s} - x_s) \tag{9}$$

where C_d is the damping coefficient, K_s is the series spring stiffness and d_{0s} is its free length. From Fig. 4

$$x_g = x_s + x_{_N} \tag{10}$$

based on Eq. 9 and 10

$$x_g = (d_{0s} - \frac{F_{ank}}{K_s}) + x_{_N} \tag{11}$$

therefore $\dot{x}_{_N}$ is

$$\dot{x}_{_N} = \dot{x}_g + \frac{\dot{F}_{ank}}{K_s} \tag{12}$$

using Eq. 2 together with Eqs. 8 and 12, the required motor power P_m is

$$P_m = (F_{ank} + C_d \dot{x}_{_N})(\dot{x}_g + \frac{\dot{F}_{ank}}{K_s}) \tag{13}$$

The required motor energy E_m is the integral of absolute required motor power over a cycle time (see Tab. I)

$$E_m = \int |P_m| dt \tag{14}$$

Human ankle gait power can be both negative and positive [9, 19]. When it is negative, a resistance motion is applied to the ankle, and when it is positive, a propelling motion is applied [1]. A motor unit cannot typically provide negative power [1, 20], therefore it must provide power to both resist and propel human motion [1, 20]. Therefore, we considered absolute values of PP and ER requirements in this study (see [1]). For this reason, an absolute value in Eq. 14 is used. In Eq. 7 and Eq. 13, the required motor power P_m is dependent on spring stiffness K_s and damping coefficient C_d. The F_{ank} and x_g are obtained by human ankle data [9, 19] and geometrical dimensions of actuation concept (Fig. 2a or [6, 7]). Thus, stiffness K_s and damping coefficient C_d become the only parameter that would influence the required motor power. For spring stiffness a range of 1kN/m to 500 kN/m (1 kN/m step size) was considered and for the damping coefficient a range of 25 Ns/m to 50 kNs/m (25 Ns/m step size) was selected. For each combination of K_s-C_d, the required motor power was obtained based on Eq. 7 and Eq. 13. Then the results were compared between K_s-C_d combinations and then the K_s-C_d values that result in minimum PP (peak power) or ER (energy) requirements were selected. A same method and range was used to determine minimum ER requirements for different actuation concepts and gaits.

III. Results

The power calculations are done both for the case the motor is assumed as an ideal power source, and the case when ball screw efficiency, motor inertia and efficiency are also taken into account. Aside from rising the required peak power (which is important from design perspective), taking into account system efficiency or inertia was not changing the nature of the findings. Thus, in this section we show the results for the case when motor is assumed as an ideal power source. This is also close to these studies [1, 12, 14], in that, makes the results more general and independent of the electromechanical properties of an actuation concept.

This section is divided in two subsections. As first approach, we searched for the minimum motor PP requirements (approach PP) and as second approach we searched for the minimum motor ER requirements (approach ER) of the SEA, SEDA and PEDA actuation concepts in normal level walking, ascending and descending the stairs. Their corresponding energy (for PP approach) or peak power (for ER approach) requirements are also discussed in this section. Calculations are done based on previous section and the results will be compared here. Furthermore the values of spring stiffness and damping coefficients which minimize motor PP or ER are tabulated in Tab. II-III. Body mass is taken 75kg.

A. Comparison of minimum motor PP (and their corresponding energy) requirements

For this approach, the minimum required motor PP and their corresponding energy requirements are shown in Fig. 5 (for SEA, SEDA and PEDA concepts and for previously mentioned gaits). The K_s-C_d values for this approach are in Tab. II.

A.1: Level ground walking

For level walking, in Fig. 5 and Tab. II, SEA concept plays the key role for minimum required PP. The damper values for SEDA and PEDA suggest that for minimum required PP, damping characteristic is not desired. Therefore, the optimal ultimate configurations of either SEDA or PEDA is already an SEA for level ground walking.

For this gait (and also stair ascent), in SEDA or PEDA concept we could not reach a result in the range mentioned for damper, so we decreased the lower limit and increased the upper limit, even in this condition the result was always at the limit. Therefore, we wrote those numbers shown in Tab. II (i.e. to 0 or to ∞, also in Tab. III).

A.2: Ascending the stairs

For ascending the stairs, shown in Fig. 5 and Tab. II, similar to level ground walking, SEA concept again plays the key role for this gait and for a minimum required PP, damper is not required. The required stiffness value is less than the level ground case. The required minimum PP increased by 13% and the corresponding energy requirement increased by 247% compared to level walking.

A.3: Descending the stairs

Shown in Fig. 5 and Tab. II, for descending the stairs, the results are very different in comparison to previous two gaits. Here, the damping characteristics are required and lead to a minimum PP which is even less than SEA concept. The SEDA concept plays the key role for this gait. For SEDA, the required minimum PP and the corresponding energy requirement decreased roughly 50% and 26% respectively with respect to SEA. For PEDA, the minimum required PP has decreased about 23% however its corresponding energy requirement has increased about 22% with respect to SEA concept. SEDA concept required the least stiffness and highest damper values for this gait (Tab. II). Damper value in PEDA is less than SEDA concept, in contrast its stiffness value is more.

For the minimum PP approach, the stiffness reaches the highest value in level walking (Tab. II). In addition, it seems elasticity is required for all gait types for a minimum required PP, however damping shows 'gait specific' advantages. The SEA concept requires more PP for descending the stairs than ascending. In fact, SEA requires its highest PP and its lowest stiffness during descent. The stiffness value gradually decreases from level walking to stair descent in all actuation concepts.[1]

B. Comparison of minimum motor ER (and their corresponding peak power) requirements

For this approach, the minimum required ER and their corresponding peak power requirements are shown in Fig. 6 for SEA, SEDA and PEDA concepts and for level walking, ascending and descending the stairs. The corresponding K_s-C_d values for this approach are in Tab. III.

B.1: Level ground walking

In this approach, for level ground walking, shown in Fig.6 and Tab. III, SEA concept plays the key role. No benefit is found for having damping characteristics. Like minimum PP approach, in minimum ER approach, the optimal ultimate configurations of either SEDA or PEDA is already an SEA for level ground walking. Compared to minimum PP approach, for ER approach in this gait, the energy requirement decreased nearly 1.5% however the corresponding peak power requirement increased nearly 8.9%.

B.2: Ascending the stairs

For ascending the stairs (Fig. 6 and Tab. III) we see similar trend like minimum PP approach, i.e. SEA concept plays the

[1] In comparison to a direct drive (DD) concept (i.e. when actuator is consisted of only a motor without spring and damper), minimum required PP decreased nearly 58% for level walking, 40% for ascending (both by SEA concept) and 72% in descending (by SEDA concept).

TABLE II

THE OBTAINED REQUIRED STIFFNESS-DAMPING VALUES FOR DIFFERENT ACTUATION CONCEPTS IN DIFFERENT GAITS, APPROACH: MINIMUM PP.

Gait		level ground walking		Ascending stairs		Descending stairs	
Stiffness [kN/m] Damping [kNs/m]		K_s	C_d	K_s	C_d	K_s	C_d
Actuation concept	SEA	80	0	68	0	64	0
	SEDA	80	to ∞	68	to ∞	45	15.5
	PEDA	80	to 0	68	to 0	62	2.2

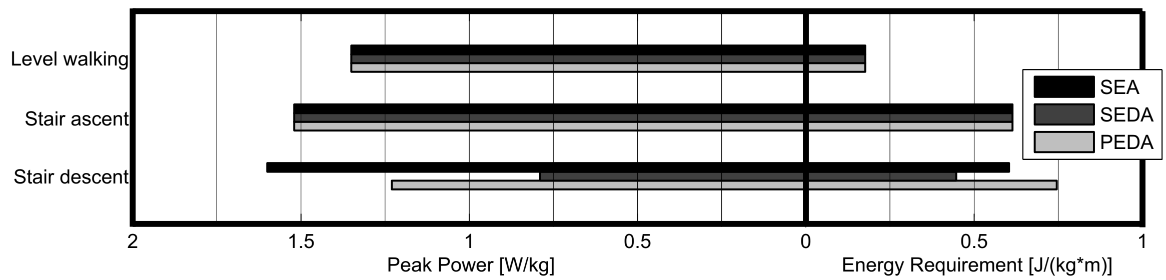

Fig. 5. The calculated required minimum peak power (PP) and their corresponding energy requirements for SEA, SEDA and PEDA in level ground walking, ascending and descending the stairs, approach: the minimum required motor PP, see also Tab. II.

TABLE III

THE OBTAINED REQUIRED STIFFNESS-DAMPING VALUES FOR DIFFERENT ACTUATION CONCEPTS IN DIFFERENT GAITS, APPROACH: MINIMUM ER.

Gait		level ground walking		Ascending stairs		Descending stairs	
Stiffness [kN/m] Damping [kNs/m]		K_s	C_d	K_s	C_d	K_s	C_d
Actuation concept	SEA	66	0	40	0	44	0
	SEDA	66	to ∞	40	to ∞	38	17
	PEDA	66	to 0	40	to 0	44	to 0

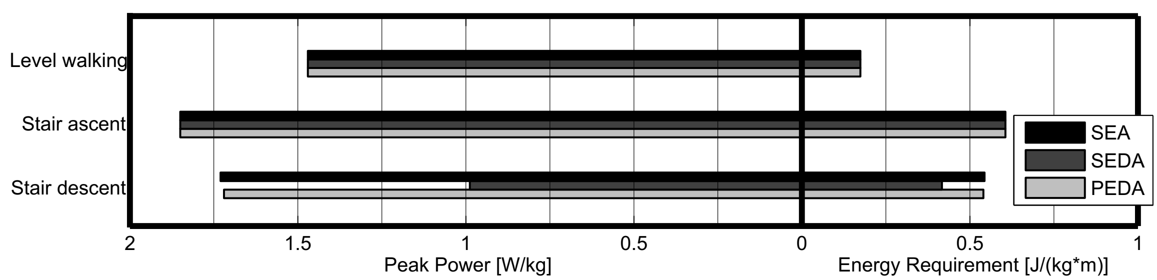

Fig. 6. The calculated required minimum energy (ER) and their corresponding peak power requirements for SEA, SEDA and PEDA in level ground walking, ascending and descending the stairs, approach: the minimum required motor ER, see also Tab. III.

key role for this gait as before and damping is not required. On the other side, the required stiffness value is less than the level ground case. The increase of required peak power is nearly 25% however the increase for ER is nearly 248% with respect to level ground walking. A Comparison to minimum PP approach (Fig. 5-Ascent) shows, for stair ascent gait in minimum ER approach, the energy requirement decreased nearly 1.4% and the corresponding peak power requirement increased nearly 21%.

B.3: Descending the stairs

The SEDA concept plays the key role for this gait (Fig. 6 and Tab. III) similar to what we observed for the minimum PP approach. The decrease of peak power is nearly 42.8% and for ER it is 23% with respect to SEA. For PEDA concept, in minimum ER approach, very slight advantage was found with respect to SEA concept and already it behaves very similar to SEA. This is the opposite of what was observed in minimum PP approach (see Fig. 5-Descent and Tab. II). For SEDA concept, the required stiffness in this gait is the least between all actuation concepts. It is similar to the trend seen in minimum PP approach.

For the minimum ER approach, the highest stiffness value belongs to level ground walking (like the minimum PP approach) and the highest required peak power or ER is for ascending the stairs. Except for SEDA, the stiffness values decreased from level walking to ascent, and increased from ascent to descent (Tab. III). In SEDA, the stiffness decreased gradually from level walking to descent. Like minimum PP approach, elasticity is always required, however damping shows required-notrequired behavior.

IV. Discussions

A. Approach for the minimum PP requirements vs. Approach for the minimum ER requirements

We found that in the approach for minimum required motor ER, the ER requirements are 'in general' only slightly less than the corresponding energy requirements of the approach for minimum required PP. In contrast, the corresponding peak power requirements increased more noticeably (Figs. 5 vs. 6). For example for ascending gait, for minimum ER approach (Figs. 6), the energy requirement decreased about 1.4% in comparison to minimum PP approach (Figs. 5), but the corresponding peak power requirement increased nearly 21% (see Figs. 5-6). Therefore, using the minimum PP approach seems a better solution for selecting the K_s-C_d values.

In Fig. 5, minimum PP and energy requirements in stair ascent increased with respect to level walking. One explanation could be that the center of mass is displaced both horizontally and vertically. In addition, the range of motion for the ankle joint is higher than level walking (Tab. I). For descent, the center of mass could use the gravity for downward motion. The passive damper also helps reduce required PP during part of stance phase where there is the first peak in ankle torque (Fig. 1). This could be an explanation why a lower power was required in SEDA in comparison to level walking. A main reason for higher energy requirements is because of the passivity of the damper. It will be discussed more in subsection IV-E.

B. Use of SEDA for the mixed gait (i.e. level walking+ascent+descent)

For stair descent, SEDA concept had the least PP requirements (Fig. 5). In this subsection we compare its PP-ER requirements and investigate whether we could use this concept for all above-mentioned gaits.

In Fig. 7 we have shown the PP and corresponding energy requirements of SEDA concept for those gaits. The K_s-C_d values are selected from Tab. II, based on discussion in IV-A. Comparing Fig. 7 with Fig. 5 shows that for level walking and ascent the minimum PP requirement increases 189% and 87% respectively in comparison to SEA concept (see Fig. 5). Increase is also seen for corresponding energy requirements. It suggests that for power-energy issues, using SEDA concept for the mixed gait is not good.

C. The spring stiffness to use in case of an SEA

For level walking or stair ascending, SEA had the least PP requirements (Fig. 5). If an SEA is going to be used for all gaits, then it would be important to know which spring to use in it (according to Tab. II, to select either from level walking, stair ascending or descending). To know this, in Fig. 8, we have shown the close-up view of the graphs for required PP versus spring stiffness in SEA for above-mentioned gaits based on Eq. 1. By these graphs we can investigate the effect of spring change on the change of required PP in SEA for those gaits. Based on Tab. II, we consider the range 60-80 kN/m. We see in Fig. 8 that for ascent gait, the required PP in this range is very slightly changing.

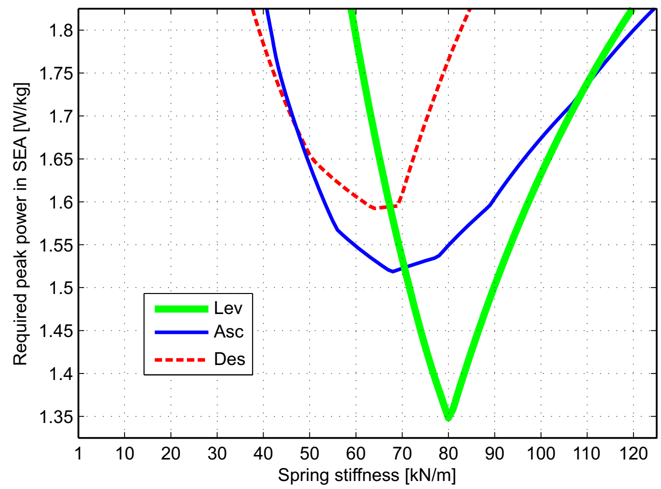

Fig. 8. The (close-up view of the) variation of calculated required PP with respect to stiffness, SEA concept, based on Eq. 1, see also Tab. II-Fig. 5.

If we take K_s=68 kN/m (the corresponding stiffness in stair ascent in Tab. II), we see that for stair descent, the corresponding required PP changes very slightly with respect to its minimum required PP, but for level walking the corresponding required PP increases to nearly 1.58 W/kg, 17% more than its minimum required PP which is 1.35 W/kg.

If we take K_s=64 kN/m (the corresponding stiffness for stair descent in Tab. II), the required PP of level walking would be nearly 1.68 W/kg, an increase about 24% with respect to its minimum PP which is 1.35 W/kg.

If we take K_s=80 kN/m (the corresponding stiffness in level walking), we see that for stair descent, the required PP would be nearly 1.76 W/kg, an increase about 10.5% with respect to its minimum PP which is over 1.59 W/kg. Hence, if the user often uses the active ankle prosthesis for a normal level walking, it is better that we select spring stiffness based on level walking and avoid the increase of required PP which was about 17-24%.

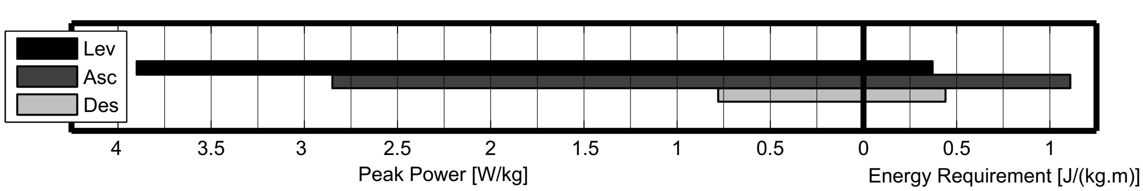

Fig. 7. The calculated required PP and corresponding energy 'IF' SEDA actuation concept is used for level walking, ascending and descending the stairs, K_s=45kN/m, C_d=15.5kNs/m, see Tab. II.

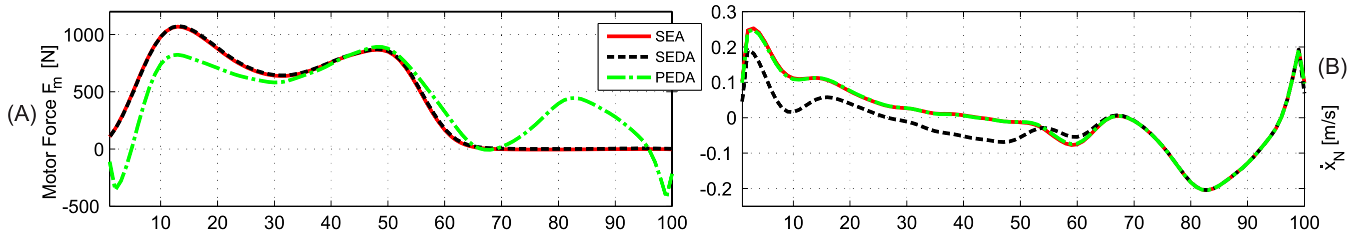

Fig. 9. The calculated required motor force F_m (A) and $\dot{x}_N$ (B) for SEA, SEDA and PEDA actuation concepts in stair descent, approach for minimum PP requirements, see also Tab. II and Fig. 5.

A more challenging design perspective is that the system is capable to change its stiffness by means of a mechanism. By this way, system will always work in minimum requirements mode for any type of gait.

D. Effect of damper on PP-ER requirements

In Fig. 9, motor force (A) and $\dot{x}_N$ (B) are shown for SEA, SEDA and PEDA in stair descent gait (approach for minimum PP, see also Fig. 5 and Tab. II). In Fig. 9A, because of damper, PEDA requires less force in comparison to SEA (or SEDA) in parts of the gait cycle which there is a need for the first peak ankle force (see also Fig. 1). On the other hand, in Fig. 9B, the $\dot{x}_N$ of SEA and PEDA are very similar to each other (It could be also understood by seeing that their K_s values are close to each other, according to Tab. II and using Eq. 12) . According to Eq. 2, the required motor power would be less as a result.

In PEDA concept, Fig. 9A, in swing phase, nearly after 65%, because of the existence of the passive damper, motor uses force in order to regulate the total force of the ankle joint. This regulating requires motor power and hence increases energy requirements in comparison to SEA. This is in agreement with Fig. 5-Descent in which PEDA required more energy than SEA. In fact because of this matter, PEDA would require quite high power during swing too (for example see the motor force and $\dot{x}_N$ at 83%). This disadvantage could be removed, if the damper in PEDA be controllable. This will be discussed in the next subsection.

For SEDA concept, the motor force is the same however $\dot{x}_N$ is less than SEA (or PEDA) for some part of the gait cycle. According to Eq. 2, this results in reducing the required peak motor power. Unlike PEDA, as motor force is very negligible in swing for SEDA, power is consequently negligible in this phase, and hence in total, energy requirement is also less than SEA (see Fig. 5-Descent).

E. Use of damper

The main objective of this study was to investigate on the effects of spring and passive damper on the PP-ER requirements in an active ankle prosthesis during level walking, stair ascent and descent. We didn't find benefit for having a damper in a powered ankle prosthesis for level walking and ascent, in contrast, for stair descent it had benefit for minimum PP or ER approach. According to these points and the result from IV-B, from the PP-ER perspective, this means in general a damper might not be required.

On the other side, [14] discussed that damping characteristic is embedded in human muscular structure and it is required for stability and adaptivity of muscular activities. These two points raise a question about the functionality of the damper in ankle. It might show that damper has an 'on demand' or 'task specific' functionality i.e. when it is required it comes into action, otherwise it is off. Having these points in mind, we probably can use a SEDA or PEDA concept instead of an SEA, that its damper is controllable (i.e. a controllable damper). By this method, damper could be off when not required (for example a normal walking) and be on when required for example for stair descent or when a sudden stop of ankle motion is required. A point for a variable damper is the control effort used for such a purpose. This could be a continuation to this study.

One important point, is that energy in damper is dissipated. An efficient design approach is that to have a mechanism that could have a same effect (reducing F_m or $\dot{x}_N$, Fig. 9) like damper but instead could use this effect to generate energy out of that (energy harvesting). By this approach, instead of wasting energy, it could be stored and provided for other joints or other occasions that there is a need for.

In Tab. II, we see that the interval of damping value in SEDA is from 15.5 kNs/m to ∞. It means that, if we would have a controllable damper in SEDA, it should be always 'on' to change damping coefficient between the limits of the interval for different gaits, meaning that there is always a need for controlling it and providing energy for this purpose.

In contrast, for PEDA it is from 0 to 2.2 kNs/m. It means that a controllable damper in PEDA could be off for a gait cycle (e.g. level walking) or for a part of gait cycle (e.g stair descent) and consequently we could avoid energy consumption for it. Therefore, in this respect, a PEDA concept might be more favorable from design perspective for powered ankle prosthesis.

According to IV-C, it was concluded that finally K_s=80 kN/m was a better compromise to be used in SEA. Based on previous paragraph, if we want to have a PEDA concept based on this SEA, that could have a controllable damper for descent gait, there remain two parameters. One is the damper coefficient and the other is the gait percent in which the damper should get 'off'. For PEDA concept, we have done the simulation (based on Eq. 13, for stair descent), and it was found that a damping coefficient of $\sim$1.98 kNs/m would be required from 1-44% of the gait cycle. After 44%

the damper could be off until 100% of the stair descent gait.

In this case, the required PP and the corresponding energy requirement would be 1.28 W/kg and 0.5 J/(kg.m) respectively. Compared to PEDA concept at Fig. 5-Descent, the required PP would increase only 4% but the energy requirement would decrease nearly 33%. From IV-C, we see an SEA required nearly 1.76 W/kg for stair descent at K_s=80 kN/m (Fig. 8). It means by using PEDA in the above-mentioned way, required PP decreases by 27% in stair descent in comparison to SEA (Fig. 8).

By this approach, it might be possible to have a powered ankle prosthesis that though not perfect, but would work in a compromise condition for all gaits. For level walking and stair ascent it is an SEA and for stair descent, with a controllable damper, it would reduce energy requirements.

Previously mentioned, a more efficient and challenging design approach is to have controllable spring and damper in the system. This makes the system operate with minimum requirements for all gaits.

V. Conclusion and Future Work

In this paper we investigated whether or not a passive damper would reduce peak power (PP) and energy (ER) requirements in an active ankle prosthesis. To do this, aside from SEA, we introduced SEDA and PEDA concepts that other than spring have damper in series or parallel to motor. We calculated the minimum PP-ER requirements of these concepts in normal walking, ascending and descending the stairs. We found that like spring, a passive damper could also have a major role to reduce PP-ER. But, we found that it was favorable for descent gait and SEDA had the least PP-ER requirements. However, for a mixed gait of level walking+ascent+descent still an SEA concept was the best compromise regrading power-energy issues. On the other side, studies showed that damping is required for stable muscular activities. This raises a question for the functionality and control method of the damper in muscle to provide stability and adaptivity for the human gait. Therefore, we suggested to have a controllable damper together with SEA. By this approach, it might be possible to have a powered ankle prosthesis that would work in a compromise condition for all gaits. For level walking and stair ascent it is an SEA and for stair descent, with a controllable damper, it would reduce energy requirements in comparison to an only SEA system.

VI. Acknowledgement

This work was supported by DFG (German Research Foundation) grant SE1042/8. The authors acknowledge S.W. Lipfert and Prof. R. Riener for providing human data.

References

[1] K. W. Hollander, R. Ilg, T. Sugar, and D. Herring, "An efficient robotic tendon for gait assistance," *ASME Jour. of. Biomech. Eng.*, vol. 128, pp. 788–791, 2006.

[2] S. Au, "Powered ankle-foot prosthesis for the improvement of amputee walking economy," Ph.D. dissertation, MIT, 2007.

[3] F. Sup, H. Varol, J. Mitchell, T. Withrow, and M. Goldfarb, "Self-contained powered knee and ankle prosthesis: Initial evaluation on a transfemoral amputee," in *IEEE ICORR*, 2009, pp. 638–644.

[4] W. Shiqian, W. van Dijk, and H. van der Kooij, "Spring uses in exoskeleton actuation design." in *IEEE ICORR*, 2011.

[5] P. Cherelle, A. Matthys, V. Grosu, B. Vanderborght, and D. Lefeber, "The amp-foot 2.0: Mimicking intact ankle behavior with a powered transtibial prosthesis," in *IEEE BioRob*, 2012, pp. 544 –549.

[6] M. Grimmer, M. Eslamy, S. Gliech, and A. Seyfarth, "A comparison of parallel- and series elastic elements in an actuator for mimicking human ankle joint in walking and running," in *IEEE ICRA*, 2012, pp. 2463–2470.

[7] M. Eslamy, M. Grimmer, and A. Seyfarth, "Effects of unidirectional parallel springs on required peak power and energy in powered prosthetic ankles: Comparison between different active actuation concepts," *IEEE RoBio*, pp. 2406–2412, 2012.

[8] B. McFadyen and D. Winter, "An integrated biomechanical analysis of normal stair ascent and descent," *Journal of biomechanics*, vol. 21, no. 9, pp. 733–744, 1988.

[9] R. Riener, M. Rabuffetti, and C. Frigo, "Stair ascent and descent at different inclinations," *Gait & posture*, vol. 15, no. 1, pp. 32–44, 2002.

[10] H. Lin, T. Lu, and H. Hsu, "Comparisons of joint kinetics in the lower extremity between stair ascent and descent," *Journal of Mechanics*, vol. 21, no. 01, pp. 41–50, 2005.

[11] K. Pfeifer and W. Banzer, "Motor performance in different dynamic tests in knee rehabilitation," *Scandinavian journal of medicine & science in sports*, vol. 9, no. 1, pp. 19–27, 1999.

[12] A. Hill, "The heat of shortening and the dynamic constants of muscle," *in Proceedings of the Royal Society London*, pp. 136–195, 1938.

[13] D. Haeufle, M. Günther, R. Blickhan, and S. Schmitt, "Can quick release experiments reveal the muscle structure? a bionic approach," *Journal of Bionic Engineering*, vol. 9, no. 2, pp. 211–223, 2012.

[14] D. Haeufle, S. Grimmer, and A. Seyfarth, "The role of intrinsic muscle properties for stable hopping—stability is achieved by the force–velocity relation," *Bioinspiration&biomimetics*, vol. 5, no. 1, 2010.

[15] H. Herr, S. Au, P. Dilworth, and D. Paluska, "Artificial ankle-foot system with spring, variable-damping, and series-elastic actuator components," Jan. 11 2012 US Patent App. 13/348,570.

[16] H. Mauch, "The development of artificial limbs for lower limbs." *Bulletin of prosthetics research*, pp. 158–166, 1974.

[17] [Online]. Available: www.endolite.com

[18] A. LaPrè and F. Sup, "A semi-active damper design for use in a terrain adaptive ankle prosthesis." ASME IMECE, 2011.

[19] S. Lipfert, *Kinematic and dynamic similarities between walking and running*. Hamburg: Verlag Dr. Kovac, 2010, ISBN: 9783-8300-50308.

[20] J. Shigley and C. Mischke, *Standard handbook of machine design*. McGraw-Hill, New York, 1986.