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On the use of (lockable) parallel elasticity in active prosthetic ankles.

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Abstract— **New challenges arise when investigating the use of active prostheses for lower limb replacement, such as high motor power requirements, leading to increased weight and reduced autonomy. Series and parallel elasticity are often explored to reduce the necessary motor power but often the effect on the energy consumption of the prosthesis is not directly investigated, as the mechanical power properties are examined yet the motor and gearbox dynamics and efficiencies are not considered. This paper presents the investigation of a parallel elasticity compared to a series elastic actuation system used in an active ankle prosthesis. Using a matched electromechanical model of the actuator shows that the electrical efficiency can be influenced using parallel elasticity. The optimal configuration depends on the motor characteristics (dynamic behavior) and limitations, which should always be taken into account when designing optimal series and parallel springs. It has been shown that adding parallel elasticity allows to reduce the required gear ratio and thus associated friction and inertial losses. Allowing the parallel elasticity to be lockable can further influence the behavior and allow for a more versatile actuator.**

I. Introduction

Including a parallel spring mechanism to an actuator can reduce torque and power requirements, especially when providing a cyclic load. Often the design objective in those only take mechanical properties into account and use non-linear behaviors and cams to better approximate the target stiffness [1], [2], [3].

Wang et al. [4] investigated the effect of series and parallel elasticity on exoskeleton actuators, however their results can be expanded to prosthetic designs as they start from the same biomechanical target. They took peak torque and mechanical power into account, and concluded that for the ankle joint a Parallel Elastic Actuator (PEA) can reduce the peak torque by 48% and Series Elastic Actuator (SEA) can reduce the motor (mechanical) power by 79%. They conclude that when using a PEA, there is no advantage of using a series spring for further mechanical power efficiency, however it might be selected for a different reason like force or torque control or lowering the output impedance. Also Grimmer et al. [5] investigated the effects of PEA and SEA, as well as a combination of both, on peak torque and energy requirements of an ankle actuator. They conclude that the energy requirements are the lowest for SEA while the PEA results in a lower peak torque.

In [6], the use of a parallel spring is investigated for the ankle prosthesis that is the subject of this research work. The objective is to reduce the peak torque the actuator in the ankle, which is a Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator (MACCEPA), needs to provide and investigate the (mechanical) peak power requirements. The investigation shows that when a unidirectional parallel spring is optimized to reduce the torque requirements, optimizing the MACCEPA series spring cannot further reduce the peak power or the mechanical energy requirements. The opposite case, where the MACCEPA and more specifically the series spring in it is optimized for a minimum of mechanical peak power, shows that the peak torque can be further reduced by adding the parallel spring. However, by only looking at the mechanical properties this cannot be thoroughly investigated because of the influence on the required motor velocity which might lead to unfeasible solutions.

Lockable parallel elasticity is something that has been investigated in prosthetic knee actuators [7], [8] given the clear elastic and high stiffness behavior during the early stance phase. In prosthetic ankles the use case is less clear, however multiple researchers investigated lockable or adjustable elasticity in a so-called semi-active prosthesis [9], [10]. In this case this is technically not a parallel spring (as there is no motor in parallel to the spring) however the functionality is very similar.

None of the previous approaches take motor dynamics and limitations into account. In Verstraten et al. [11] the friction, inertia and gearbox efficiency are taken into account when examining the effect of series and parallel elasticity on the characteristics of actuators providing the same behavior as a healthy ankle joint. Different optimized parameters are achieved depending on the optimization criterium: mechanical peak power, electrical peak power, mechanical energy consumption and electrical energy consumption. Because of the inverse dynamic simulation, it is difficult to assess the motor constraints and limitations as well as and the effect of those on the output. Because of the engagement of the unidirectional spring, the setpoints the motor needs to follow in order to reproduce the desired torque is not continuous. This causes a jump in the required velocity (see Figure 2) and an infinite acceleration peak, which introduces a tracking error in the motor. This makes it difficult to calculate the effect of the inertia on the current. Here a dynamic model of the CYBERLEGs ankle actuator is used to investigate the feasibility and efficiency of adding a parallel spring to the ankle SEA system, taking into account the motor dynamics and efficiencies. Different approaches were investigated:

- Adding a parallel spring to the original ankle system with the series spring and precompression that were the result of the optimization by means of minimizing mechanical power. Adding the parallel spring will decrease the peak torque that needs to be provided by the

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MACCEPA.
- Optimize both series and parallel elasticity to minimize the overall energy consumption of the system when providing the same behavior as a healthy ankle during the gait cycle.
- Investigate the effect of a lockable parallel spring.

This research paper presents the materials and methods that have been used for the investigation: a series and parallel elastic actuator of which a dynamic electromechanical model was built and tuned based on experimental data, and the optimization criteria that have been used for the investigation. The results for the parallel elasticity optimization are presented in comparison to different optimization criteria for a series spring according to the state-of-the-art and compared in terms of electrical efficiency.

II. Materials and Methods

A. Series and Parallel elastic actuator

The actuator used for this investigation is based on the MACCEPA-design as described in [12]. It is an actuator with variable compliance which allows to change this compliance without changing the equilibrium position of the actuator. The actuator, which was designed within the CYBERLEGs project, is based on rigid linkages and a sliding mechanism as described in [13]. The specific mechanical structure of this actuator is important for the implementation in the dynamic model, yet the results are not limited to this specific layout. The approach is consistent for the mechanical structure of any SEA or PEA, which converts a motor output angle into a specific torque behavior.

The actuator described in [14] has been redesigned and equipped with a parallel spring for this investigation. The mechanism of the ankle prosthesis actuator can be seen in Figure 1, as well as the implementation in the ankle-knee prosthesis which has been extensively tested with a number of amputees for various tasks, including level walking but also stair climbing, sit-to-stand tasks and others.

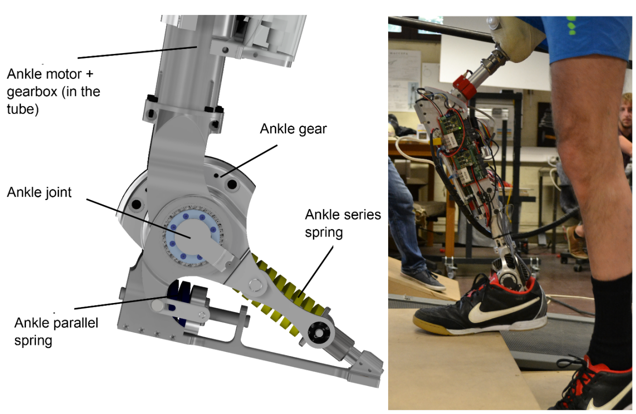

Fig. 1. Mechanism of the ankle prosthetic actuator that is used for this investigation (left). Implementation of the mechanism in the functional ankle-knee prosthesis, able to perform a large variation of tasks (right).

B. Dynamic actuator model

The dynamic model used in this work is based on the model of the SEA constructed in [14] by adding and fitting the driver dynamics and the PID-controller of the system to the electromechanical model. This model has been fit to an extensive set of measurements performed in a test bench. This is necessary to achieve an accurate estimation of the motor dynamic behavior and electrical energy consumption. The need for this dynamic model is shown by calculating the motor setpoints for the actuator including a parallel elasticity. Figure 2 shows the behavior of the MACCEPA actuator, with and without parallel spring, providing a healthy walking output characteristic. The motor position setpoint shows a discontinuity when engaging and disengaging the unidirectional parallel spring. This results in a jump in target velocity for the motor. An inverse dynamic simulation is incapable of handling such discontinuity and requires a workaround. Using the dynamic model, which is tuned to represent the behavior of the investigated actuator, solves this problem.

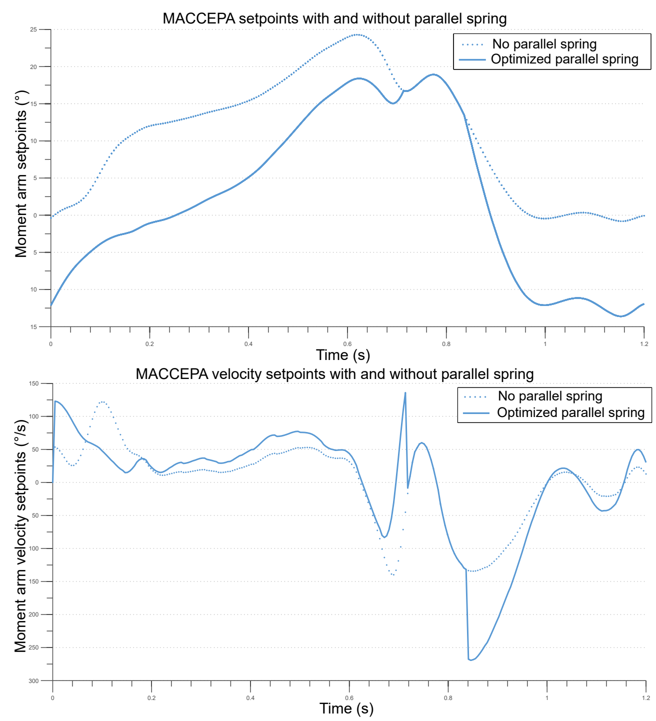

Fig. 2. Motor setpoints and velocities for an actuator without and with optimized parallel spring. The graph shows the discontinuity in the position setpoint and jump in required motor velocity. An inverse dynamic simulation is not capable of handling such discontinuities and an approximation needs to be made. Using the tuned dynamic model makes sure the behavior of the model is representative for the investigated actuator.

The dynamic simulink model including the torque due to the parallel spring is shown in Figure 3.

C. Parallel spring optimization

The parallel springs that have been considered are unidirectional springs which provide a linear torque around the ankle joint, so with a constant angular stiffness, as can be

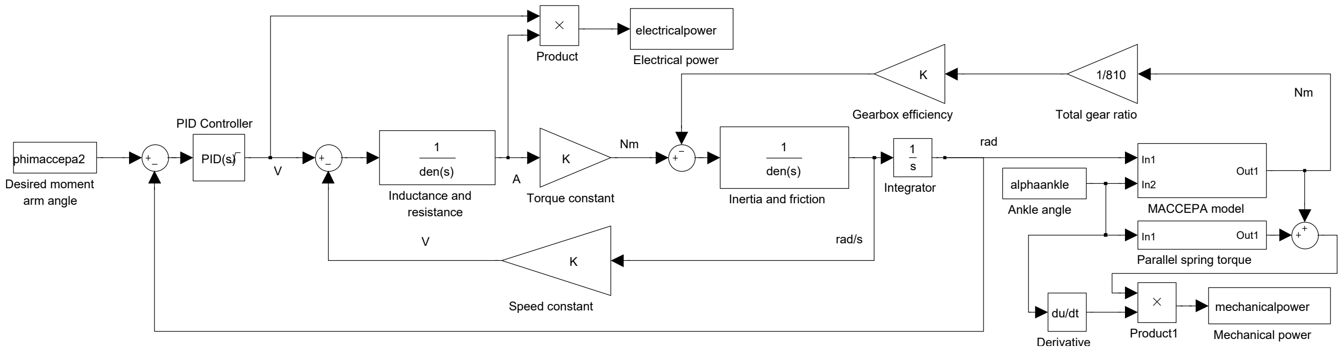

Fig. 3. Overview of the Simulink model with the addition of the parallel spring torque. The moment arm angular position and angular position of the joint are used as inputs, the mechanical and electrical power can be calculated from the model. The parallel spring torque is added to the torque calculated from the MACCEPA model, and the total torque is used to calculate the mechanical energy.

seen in Figure 4. Both the parallel spring stiffness k_{ps} and the angle of engagement $\theta_{ps,0}$ were varied to investigate the influence of both. Figure 4 shows an example of the parallel spring torque compared to the biomechanical torque. The method used to find the optimum is a brute force search when varying the variables relevant for the parallel spring ($\theta_{ps,0}$ and k_{ps}) were investigated within the following range:

$$-20^{\circ} \leq \theta_{ps,0} \leq 10^{\circ} \tag{1}$$

$$0Nm/^{\circ} \leq k_{ps} \leq 10Nm/^{\circ} \tag{2}$$

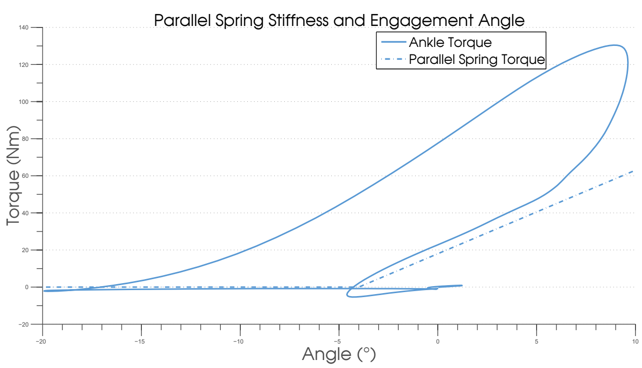

Fig. 4. Parallel spring torque around the ankle compared to the biomechanical torque. In the simulations, the parallel spring stiffness k_{ps} and the angle of engagement $\theta_{ps,0}$ are varied to cover the entire range.

The results over this range are investigated for the following criteria:

- Minimum peak and average torque
- Minimum electrical energy (maximum efficiency)

In a first definition of the ankle actuator, a set of requirements were found by optimizing mechanical properties, such as mechanical energy and power [15]. This is a common practice when optimizing series an parallel elastic elements [3][5][2], however it is neglecting important effects like motor efficiency and how this changes for different velocities and torques. For this reason, such an optimization will not necessarily lead to an optimum in electrical energy or power, which is in the end what determines battery and motor size [16]. An optimization of the series spring of the discussed actuator resulted in a second set of parameters which led to a minimum in the energetic consumption [14]. These two sets of parameters are used as a starting point to investigate the effect of adding parallel elasticity, and to verify if state-of-the-art methods converge to similar optimums compared to the methods used in this work. An overview of the setpoints of the SEA can be found in Table I.

TABLE I

OPTIMIZED PARAMETERS FOR THE SEA, WHICH HAVE BEEN USED AS INPUT FOR THE OPTIMIZATION OF THE PARALLEL ELASTICITY AS USED IN THIS WORK. THE DETAILS FOR THE OPTIMIZATION FOR PEAK MECHANICAL ENERGY CAN BE FOUND IN [15], THE DETAILS FOR THE OPTIMIZATION FOR ELECTRICAL ENERGY EFFICIENCY CAN BE FOUND IN [14]

Optimization type for SEA	Gear ratio	Series spring constant (kN/mm)	Electrical energy efficiency
Peak mechanical energy	86:1	130	16%
Electrical energy efficiency	86:1	30	25%

III. RESULTS

A. *Minimum peak and average torque*

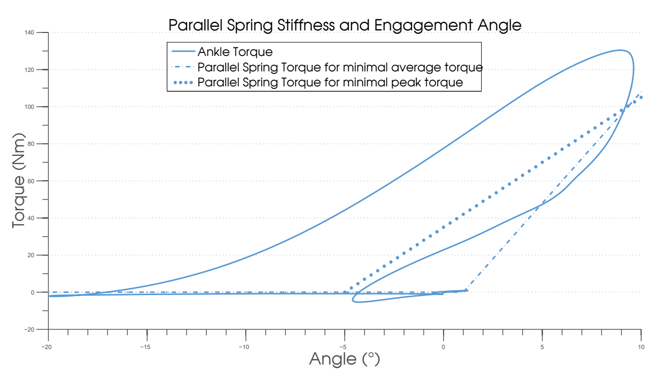

Fig. 5. Parallel spring behavior based on a minimization of the peak torque and the average torque. The series springs will be added and the influence on the energy efficiency is investigated.

The first optimization is done using purely mechanical properties, and is only linked to the output characteristic that needs to be provided by the actuator. Literature describes that looking at the mechanical properties of a PEA, it is not worth adding a series spring from an energetic point of view [4], [6]. We investigate an optimized parallel spring, meaning the torque profile is minimized, and see if the series compliance can provide any additional benefit. The parallel spring is mainly optimized to minimize the peak torque in the ankle, yet minimizing the average torque could also be an objective. Figure 5 shows both parallel springs optimized for a minimal peak torque and minimal average torque. It can be observed that the peak torque generated by the springs in both cases is similar at around 110 Nm, yet they have a difference in engagement angle: the optimization for minimal average torque results in an engagement angle of 1 degree while the optimization for minimal peak torque results in an engagement angle of -5 degrees. The difference lies with the behavior of the ankle around the first ground contact, where there is a small negative torque preventing the foot to slam against the ground (drop-foot). Because of this behavior, the ankle will have to fight against the parallel spring at this point.

B. Minimum electrical energy

The second optimization criterium we investigate looks for the minimum electrical energy or the highest electrical efficiency. As explained before, two different cases are considered: one where the SEA has been optimized for mechanical energy and the other where it has been optimized for electrical efficiency.

1) SEA optimized for minimum mechanical energy: The results of the optimization can be seen in Figure 6, starting from the SEA system optimized for minimum mechanical energy. The graph shows the efficiency of the original system at the boundaries, so a parallel spring with stiffness 0 or an engagement angle of 10°. Even though most parallel spring configurations lead to a lower efficiency, there is a subset of parallel springs which increase the energy efficiency by about 4%.

One of the consequences of adding a parallel spring is that, as the peak torque is reduced, the actuation system overall gear ratio can be reduced, allowing for higher velocity, yet also reducing the reflected inertia and possibly reducing losses in the gearbox system. This has been investigated by performing the same simulation yet reducing the motor gearbox ratio from 86:1 to 33:1. The results can be seen in Figure 7. The graph shows that the original SEA system was not able to perform the task with this gear ratio, as the solution without parallel spring does not lead to a reasonable result. There is a set of parallel springs however which leads to an overall efficiency which is higher than what was achieved before (around 22%).

2) SEA optimized for minimum electrical energy: The results for the optimization can be seen in Figure 8, starting from the SEA system optimized for minimum electrical energy. The graph shows the efficiency of the SEA system

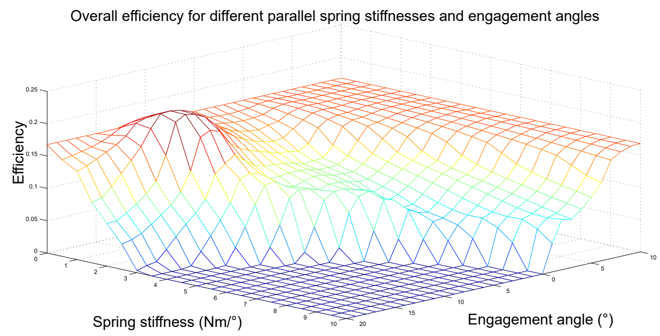

Fig. 6. Efficiency of the actuator for different k_{ps} and $\theta_{ps,0}$ when adding a parallel spring to the original MACCEPA system which had been optimized for mechanical energy. The original system had an energy efficiency of around 16%. The efficiency drops for most parallel springs, yet there is an optimal region with an efficiency increase, with a maximum of 20%. The electrical energy consumption drops from around 80 to 50 J per step for parallel springs with a stiffness of around $1-2Nm/°$ and an engagement angle of between -10 and -20 degrees.

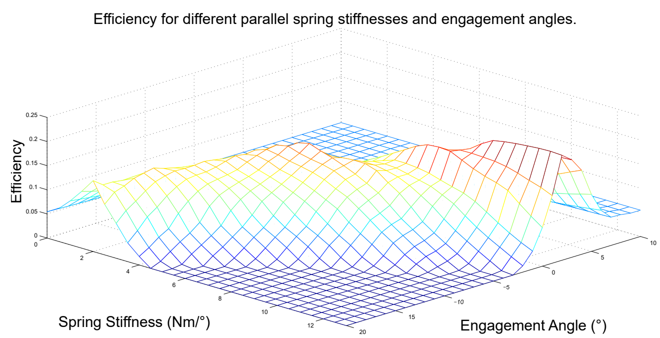

Fig. 7. Efficiency of the actuator for different k_{ps} and $\theta_{ps,0}$ with a motor with gearbox 33:1, starting from the MACCEPA optimized for peak mechanical energy. Without or with a soft parallel spring, the actuator is not able to provide the required torque. The peak efficiency is almost 22%.

when looking at a 0 stiffness parallel spring, which is around 25%. The results show that the efficiency can be marginally improved by adding a parallel spring, indicating that the optimized SEA system already reached the highest possible efficiency for the desired output characteristic.

Similarly as before, we can also investigate the effect of lowering the gear ratio to the optimal parallel spring and the efficiency. Figure 9 shows that indeed the efficiency can again be marginally improved, which can be linked to the lower gearbox losses and decreased inertial effects.

3) Lockable parallel spring: In all of the above cases, linear unidirectional springs with fixes engagement angles and stiffnesses have been investigated. Looking at the achieved results and the healthy walking behavior that is being approximated, it can however be interesting to consider an unidirectional spring which can be unlocked from the system. This behavior is similar to what has been described for a knee prosthesis in [7] and later for a knee orthosis in [17] and can be created using a similar mechanism. The advantage of the lockable parallel spring becomes clear when looking at Figure 10.

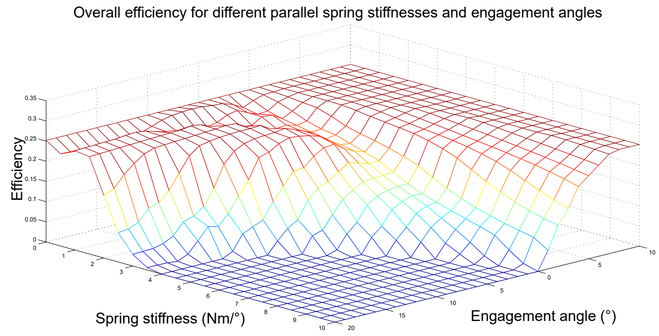

Fig. 8. Efficiency of the actuator for different k_{ps} and $\theta_{ps,0}$ in case of the MACCEPA optimized for minimal energy consumption first. By adding the parallel spring, the efficiency can be slightly improved by 0.5% but there is no significant benefit.

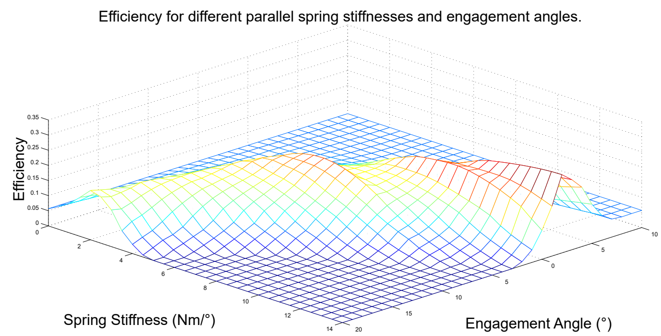

Fig. 9. Efficiency of the actuator for different k_{ps} and $\theta_{ps,0}$ in case of the lower gear ratio (33:1). The optimization for energy efficiency of the actuator without parallel spring is not possible as the system cannot provide the necessary torque. By optimizing both the series and the parallel spring, an efficiency of about 26% is achieved, which is marginally higher than the system with higher gear ratio.

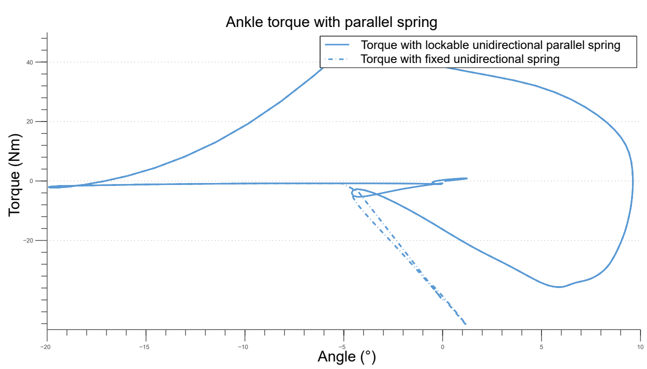

Fig. 10. Parallel spring behavior comparing a lockable and a fixed unidirectional spring. Using the lockable spring can eliminate the undesired negative peak torque at the initial ground contact.

Whereas parallel springs with an engagement angle smaller than 0° cause a negative torque peak which needs to be overcome by the actuator to avoid the foot hitting the ground hard at initial contact (similar to a drop-foot situation), using a lockable parallel spring could allow to overcome this. This is also expected to have an influence on the energy efficiency of the system. This is shown in Figure 11, where the lockable spring is used in combination with the system where the highest efficiency has been simulated, being the SEA optimized for energy efficiency with a reduced gear ratio. The advantage of the lockable parallel spring could be beneficial roughly between $-5°$ and $0°$ of the ankle, which is clearly visible when comparing to Figure 7, where the efficiency drops between these angles. The lockable parallel spring mechanism was investigated for the system with gear ratio of 33:1 and for the spring engagement angles between $-5°$ and $0°$, and Figure 11 shows that the efficiency can indeed be greatly improved in this region by using a lockable unidirectional spring.

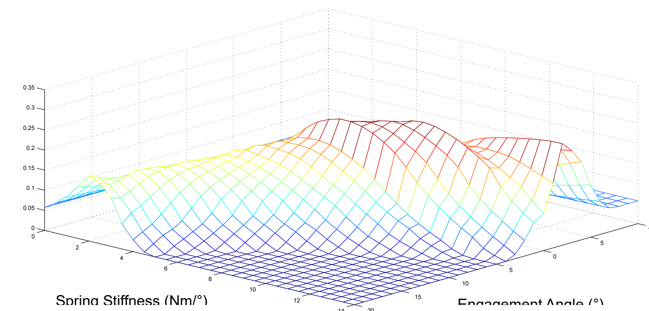

Fig. 11. Efficiency of the MACCEPA system with a lockable parallel spring used for $\theta_{ps,0}$ between 0° and $-5°$. The efficiency in this region can be greatly increased by using the locking mechanism, increasing the efficiency to over 26 %.

IV. Discussion

The model was used to track a healthy biomechanical behavior, and the energy optimization was done for this behavior. While no person will walk exactly like this healthy behavior, and especially no amputee, it is believed that being able to provide torques and velocities in the ankle joint that are very similar to the ones used in this work is vital to being able to fully restore a healthy and symmetric gait pattern for amputees. Simulating the actuator behavior in this manner allows a deviation from the healthy human gait, which is why the energy efficiency was looked at rather than the electrical energy consumption. When the motor fails to track the desired output for the ankle joint perfectly, the mechanical energy input drops as well as the electrical energy.

The simulated efficiencies do not necessarily correspond to the efficiencies that can be measured during amputee experiments, and similarly the optimums will not necessarily be the same. This is because the amputee walking pattern for level walking will diverge from the average used in this work, but also because the situation will be very different for up- or downslope walking, where the parallel spring could hinder the movement or have no effect at all. For cases like this, the lockable parallel spring can have a major advantage over the fixed spring as it can be controlled to take this into account. Besides these arguments, idle standing/sitting is a major part of the daily activities, and selecting a parallel

TABLE II

RESULTS OF THE OPTIMIZATION OF THE PARALLEL ELASTICITY FOR ENERGY EFFICIENCY, STARTING FROM DIFFERENT OPTIMIZATIONS OF THE SEA. THE PARALLEL ELASTICITY CAN IMPROVE THE ENERGY EFFICIENCY AND ALLOW FOR A LOWER GEAR RATIO, HOWEVER WHEN THE SEA IS OPTIMIZED FOR ENERGY EFFICIENCY, THE EXTRA POSSIBLE GAIN IS MINIMAL. COMPARE TO TABLE 1 FOR REFERENCE.

Actuation type	**Optimisation method for SEA**	**Gear ratio**	k_{ps} (N/mm)	$\theta_{ps,0}$ $(°)$	**Electrical energy efficiency**
SEA+P	Peak mechanical energy	86:1	2	-12	20%
SEA+P	Peak mechanical energy	33:1	13	1	22%
SEA+P	Electrical energy efficiency	86:1	0.5	-7	25.5%
SEA+P	Electrical energy efficiency	33:1	13.5	2	26%
SEA+ lockable P	Electrical energy efficiency	33:1	9	-1	26%

spring with an engagement angle below 0° might require the motor to constantly compensate during these activities, causing an energy consumption over the course of a day which is much higher than the gain of having the parallel spring.

The reported efficiencies, even after optimization, might seem low (26 % at maximum). This is however closely linked to the trajectory that needs to be generated at the output, and thus cannot be compared to what is reported as the maximum efficiency of a motor. The losses of the actuator include motor losses, friction and resistance losses as well as losses in the motor driver. The efficiencies reported in this work should only be compared to those of similar mechanisms, taking all losses into account and providing the same output behavior.

V. CONCLUSION

The research presented in this paper show that a parallel elastic system optimized for minimal mechanical work, which is often done in the state-of-the-art, does not necessarily lead to an optimal electrical efficiency. There is not one optimal parallel elasticity when looking at the energy efficiency, but the system needs to be investigated in combination with motor/gearbox combination to find the optimal configuration. When a SEA system is optimized for energy efficiency, adding the parallel elasticity can only minimally improve the efficiency. Having the parallel spring lockable can minimally increase the energy efficiency of the overall system but also widen the scope of the actuator beyond just level walking.

ACKNOWLEDGMENT

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