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TOPICAL REVIEW

Biarticular elements as a contributor to energy efficiency: biomechanical review and application in bio-inspired robotics

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Abstract

Despite the increased interest in exoskeleton research in the last decades, not much progress has been made on the successful reduction of user effort. In humans, biarticular elements have been identified as one of the reasons for the energy economy of locomotion. This document gives an extensive literature overview concerning the function of biarticular muscles in human beings. The exact role of these muscles in the efficiency of human locomotion is reduced to three elementary functions: energy transfer towards distal joints, efficient control of output force direction and double joint actuation. This information is used to give an insight in the application of biarticular elements in bio-inspired robotics, i.e. bipedal robots, exoskeletons, robotic manipulators and prostheses. Additionally, an attempt is made to find an answer on the question whether the biarticular property leads to a unique contribution to energy efficiency of locomotion, unachievable by mono-articular alternatives. This knowledge is then further utilised to indicate how biarticular actuation of exoskeletons can contribute to an increased performance in reducing user effort.

1. Introduction

Research into wearable robotics has caught the eye of several groups as a means to restore compromised gait. Both the application of lower limb exoskeletons as a training machine in rehabilitation [1, 2] and as an assistive device in daily life [3, 4] is highly valued. In both cases active participation of the user is thought to be of invaluable importance [5, 6]. In rehabilitation machines, maintaining a normal walking pattern while actively participating to the robotic gait therapy is another critical factor that influences training efficiency [7]. For assistive devices energy consumption of the wearer is key [8, 9]. Assistive exoskeletons are designed for users with decreased locomotion abilities, as a means to regain (part of) their mobility in daily life. In order to be effective, they should be able to provide sufficient support to induce a reduction of user effort to manageable levels [10], thus allowing them to move around for longer periods of time. Because user exertion and onset of fatigue is strongly correlated to the energy consumed during motion, an increase in energy consumption while wearing an exoskeleton should at all times be avoided [11]. Ideally, the device reduces energy consumption of the user during movement.

Both the execution of a natural walking pattern and the energy consumption of the wearer, are strongly influenced by the mass and inertia of the exoskeleton that is positioned onto the wearer during operation [8, 12]. To reduce the mass and inertia of a rehabilitation machine, the device can be mounted onto a treadmill and heavy or bulky components can be removed from the moving parts of the exoskeleton towards the fixed base. This strategy was already applied in the Lopes II [13] and in the CORBYS rehabilitation system [14], significantly reducing the mass that is attached to the human. For assistive exoskeletons, relocating heavy components to a base frame is not possible because the device needs to be stand-alone. Therefore, the total mass of the device is a critical property. Increasing the energy efficiency of an exoskeleton decreases the need for heavy batteries and over-dimensioned motor combinations, thus reducing the total mass of the device. As such, it contributes to a positive evolution in the performance of exoskeletons.

Human locomotion is considered to be energy efficient [15] and can be used to cover long distances [16, 17] in a large variety of environments [18]. One of the reasons why this is the case is due to the exploitation of passive structures in the legs. During human locomotion, elastic energy is stored in the ligaments and tendons in certain phases and then released in other phases of the gait cycle [19, 20]. Over the years, several researchers have developed the additional theory that energy transfer between joints is another reason for locomotion efficiency [21]. Biarticular muscles, or two-joint muscles, are said to make this possible [19, 22–24].

In this paper, the literature concerning the contribution of biarticular muscles to energy efficiency, in human beings, is reviewed in section 2. Because the main contributing muscles for most human locomotion tasks are predominantly active in the sagittal plane [25–27], this review is limited to the muscles acting in that plane to avoid complicating the matter. Three distinct operating mechanisms for conserving energy are explained, as well as the contribution of biarticular muscles to these mechanisms. Although not all researchers agree that muscles need to be biarticular to contribute to any of the three mechanisms, as presented in section 2.3, they do acknowledge that the spanning of two joints simultaneously might contribute to locomotion in a way mono-articular muscles can't. In section 3, the application of biarticular elements in bio-inspired robotics is reviewed. This review confirms that biarticular elements cause beneficial influences that are not easily replicated by mono-articular actuation strategies. It is our intent, by combining biomechanical knowledge with the robotic applications, to give an insight into how mimicking biarticular muscle behaviour could improve the energy efficiency of an assistive exoskeleton and as a result positively influence the energy consumption of the wearer. This is presented in section 4. The paper is ended with concluding remarks, formulated in section 5.

2. Human biomechanics

This chapter provides the reader with a biomechanical review of the literature concerning the role of biarticular muscles in energy efficiency. The different contribution mechanism are presented in section 2.2. Because they are still the subject of discord in literature, this chapter also includes a critical view on past and present research in section 2.3.

2.1. Human musculature of the lower limbs

The human body has 244 kinematic degrees of freedom (DOF) and a conservative estimate of the amount of skeletal muscles is 630 [28]. Thus on average each DOF is controlled by 2.6 muscles. In order to move a joint, only two muscles are required: one to perform the flexion action and another to perform the extension action. Thus, the number of muscles in the human body is more than the minimum required amount [29]. Several of the muscles in the human body are biarticular, i.e. they span two joints. In the lower extremities, there are three: the Gastrocnemius, the Hamstrings and the rectus femoris. In figure 1, they are denoted as: GAS, HAM and RF, respectively. The primary mono-articular muscles that drive the joints during locomotion are depicted in green. The muscles responsible for joint extension of hip, knee and ankle are: gluteus maximus (GMAX), Vasti muscle group (VAS) and Soleus (SOL), respectively. Those responsible for joint flexion: iliacus (IL), short head of the biceps femoris (BFsh) and tibialis anterior (TA).

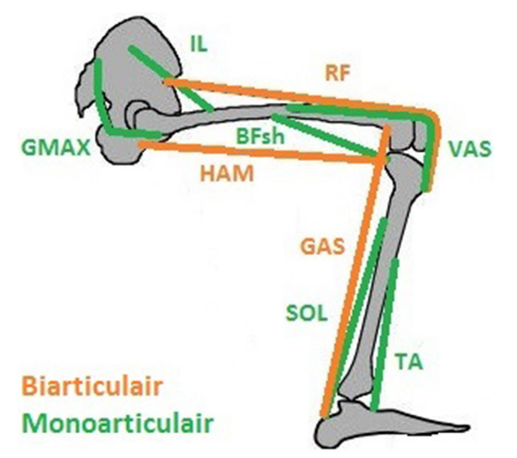

Figure 1. Main muscle groups of the lower limbs in the sagittal plane. Figure adapted from [30].

2.2. Role of biarticular muscles in energy efficiency

As mentioned in the previous section, the human body contains more muscles than required to control each DOF. The same is true for the lower limbs, as each joint can be fully controlled by use of the mono-articular antagonists alone. As such, the biarticular muscles are not strictly necessary to allow movement of the legs. Thus, they can be thought of as redundant for motion. Yet, in millions of years of evolution they have not been eliminated, indicating that they must be of benefit [31, 32]. Redundancy is advantageous for survival, as a number of different muscle activation patterns could provide the required joint torques for performing a certain task [33]. Despite this redundancy, the motor control system only selects a limited number of them to accomplish a desired task [28]. Energy efficiency, i.e. the efficient use of metabolic energy consumed to perform a certain task, has proven to be an important factor in the selection of certain activation patterns over others. Researchers were able to predict body motions, ground-reaction forces, and muscle excitation patterns for walking by use of a dynamic optimisation that minimises metabolic energy consumption per unit distance travelled [34–36]. Biarticular muscles were activated by the optimisation, reinforcing the assumption that they do play a significant role in energy efficiency of legged locomotion [19, 37].

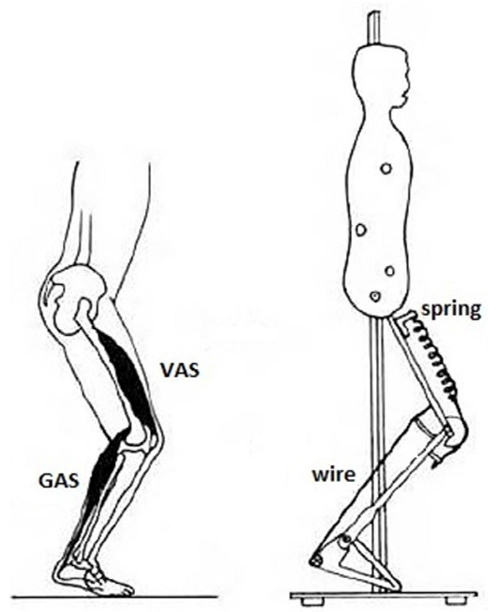

Figure 2. Jumping Jack model. The model is loaded by pushing it down, thus extending the spring. The spring represents the knee extensors, VAS. The wire represents the GAS muscle. Figure adapted from [43].

Because the role of muscles can only be understood by studying their action during movements of the entire organism [38], researchers have been studying human jumping, cycling and running [24, 25, 29, 39–42] to determine the exact way in which biarticular muscles contribute to energy efficient locomotion. These analyses have uncovered three distinct functions of GAS, HAM and RF: power transfer towards distal joints, efficient control of output force direction and double joint actuation. All of these are described in more detail in this section.

2.2.1. Proximal to distal transport of power

Biarticular muscles are said to allow the transport of energy between joints in the direction from proximal to distal ones. Van Ingen Schenau *et al* [22] experimentally demonstrated the mechanism of power transport by the GAS muscle during jumping, by using a simple physical model called Jumping Jack (figure 2).

The Jumping Jack model consists of a torso, connected to a vertical slider, and one leg that is composed of 3 flexion/extension joints: ankle, knee and hip. A spring represents the knee extensors and is loaded when the model is pushed down. A wire represents the GAS muscle and its length determines at what moment in the jumping motion the extending knee starts pulling on the foot, thus inducing ankle plantarflexion. The experiments showed that the height of the jump significantly increased, compared to the situation where there is no coupling between knee and ankle. The biarticular element thus transports the mechanical output of the mono-articular spring to a joint where it can, more effectively, contribute to the aim of the motion [22]. Other researchers observed a similar increase in jumping performance when biarticular elements were used to couple joints [44–46], and the flow of power from knee to ankle was confirmed in a simulation study by Bobbert *et al* [47]. The results showed that 25% of the peak power output in plantar flexion is power that is transported from knee to ankle, while the contracting calf muscles are responsible for another 25% and the remaining part appears to be due to recoil of elastic tissues. Voronov [48] stated that the powers of the knee and ankle joint extensors alone are insufficient for a strong and quick movement such as a high jump. Therefore, transfer of power is necessary to compensate for this physiological shortcoming. By comparing the biomechanical analysis of a high jump with several isokinetic single joint movements, Voronov showed that the force-velocity characteristics of the knee and ankle extensors are inadequate for the muscles to provide the joint powers seen in a high jump. The test results revealed that up to 200 W of power may be transported from knee to ankle during a high jump. Additionally, a similar effect of power transfer was reported between the human hip and knee joint: the RF muscle permits the hip extensor to assist in extending the knee [22, 44]. Ultimately, this means that energy can be transferred from top to bottom throughout this entire chain: *Gluteus Maximus* $\succ$ *Rectus Femoris* $\succ$ *Gastrocnemius* $\succ$ *ankle*. Thus, energy flows from proximal to distal joints [23, 29, 49].

Note that in the explanation above, the power that is transferred by the biarticular muscles is produced by the mono-articular hip and knee extensors [48]. Although biarticular muscles allow for the jumping height to increase for the same input of energy, this is not actually reducing energy consumption in a maximum height jump. However, in daily life, maximum height jumping is not likely to occur. Jumping tasks are more likely limited to jumping to or over a specific height, e.g. jumping onto or over an obstacle. Therefore, energy economy during such a task is improved when biarticulars are active, compared to the case when only mono-articular muscles are involved. Additionally, Prilutsky *et al* [23] theorised that the presence of the proximal-to-distal energy flow allows for a distribution of muscle volumes that reduces leg inertia with respect to its suspension point (i.e. the hip), and this without compromising the energy output at the ankle [24]. Such a distribution allows for the leg to move with a lower consumption of energy [23, 50, 51], also contributing to locomotion economy. As such, the transport action of biarticular muscles contributes to energy efficiency in joint extension tasks such as jumping, but also to the efficiency of general leg motion in other locomotion tasks. It is also worth mentioning that the same mechanism of energy transfer through biarticular muscles improves shock absorption in the landing phase of jumping. Due to the small muscle volumes in the distal portion of the legs, the ability to dissipate mechanical energy of the body is limited

[23]. Activation of GAS and RF, allows for energy to be transferred towards the knee and hip joint, where it is dissipated in the knee and hip extensors. Muscle activation patterns, measured during the execution of several landing tasks, support this reasoning [52].

2.2.2. *Efficient control of output force direction*

A second function of biarticular muscles was first discovered during the analysis of cycling [22, 26, 53–56]. Many authors have observed significant phases of co-activation of agonists and antagonists during cycling [32, 53, 57]. This co-activation is often denoted as uneconomical because the force contribution of these muscles is assumed to be canceled out [53]. However, Lombard [58] made a counter-intuitive claim by asserting that muscles with apparently opposing actions, termed pseudo-antagonists, can be used together in a productive way [59].

Several researchers explained the use of co-activations during cycling [22, 56]. Cycling performance is determined by the power transferred to the pedal. The instantaneous power to the pedal is equal to the inner product of the pedal force vector and the pedal velocity vector. Therefore, the more the force on the pedal is directed in the instantaneous direction of the displacement of the pedal, the more it can contribute to useful power [22, 60]. In the EMG measurements shown in figure 3, one can see that co-activation of GMAX and RF is strong during the first half of the down stroke, i.e. from 0–90°, and co-activation of VAS and HAM is most pronounced during the second half, i.e. from 90–180° (remember the electro-mechanical delay). The significance of these co-activations can be explained starting from the specific task demands in cycling: effectively transferring muscle power to the rotating pedal [22].

As explained earlier, efficient transfer of power requires the force to be aligned with the instantaneous direction of motion. In figure 4, three chronological moments (A, B and C) in the crank cycle are depicted: when the crank is in the first half of down stroke (around 45°), when it is halfway in the downward stroke (at 90°) and in the second half of down stroke (around 135°), respectively. When the pedal has travelled 90°, optimal power transmission requires the force to be directed downward, perpendicular to the pedal. It is clear that, in this case, both the force and the direction of motion required for cycling can be sustained by the hip and knee extensor moments that are shown in figure 4 example B. In the first and the second half of downward stroke however, the force needs to be in an angle different from 90° with respect to the pedal. In the first half, the force should be directed forward with respect to the pedal as shown in example A. This direction of force can only be achieved by a flexing hip moment and an extending knee moment. Yet, for the desired movement both joints need to extend. This situation could be satisfied by mono-articular

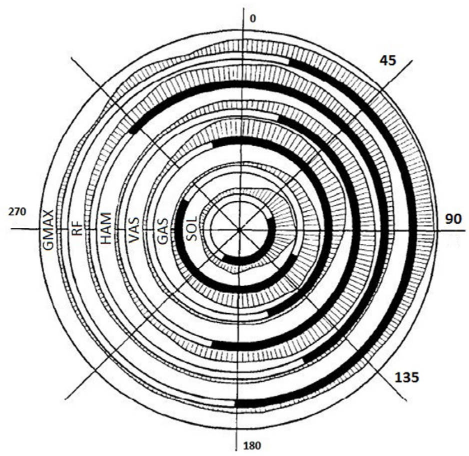

Figure 3. Average EMG signals of six leg muscles during cycling as a function of crank angle. The solid, black bars indicate the phases where the muscle shortens. The top dead centre is at 0°. For the interpretation of the activity patterns an electro-mechanical delay, i.e. delay between the change in EMG level and the change in mechanical output of the muscle, corresponding to approximately 50° should be taken into account. Figure is adapted from [22].

muscles alone, where the hip is forced to extend under the influence of an increased knee extensor torque, while the hip flexors are generating the required flexor torque. This would be extremely energy inefficient though, as energy generated by the contracting knee extensors is converted to heat in the elongating hip flexors [22, 59]. A similar dissipation would occur when a force and motion directed as in example C (second half of downward stroke) were to be provided by mono-articular muscles alone. Van Ingen Schenau *et al* [22] state that the movements in examples A and C can be performed without eccentric contractions of mono-articular muscles by simultaneous activation of the biarticular ones. In example A, the RF can ensure a flexing moment at the hip and support the mono-articular knee extensors in the required large extending moment and similarly, the HAM can provide relief in example C.

The conclusion of this analysis is that a biarticular muscle can act to accelerate one of its spanned joints into rotation opposite to its joint moment and as such prevent eccentric work of mono-articular muscles [22, 60, 61]. This conclusion is supported by other researchers, based on their own work [55, 56, 59]. Measured EMG patterns during cycling are as expected according to this conclusion: the mono-articular muscles are mainly active when they can shorten and co-activation with the biarticular muscles at those moments is visible [22, 54, 57]. Additionally, Doorenbosch *et al* [55] observed that muscle activity of the mono-articular muscles increased when position changes were added to the initial isometric force orientation trials, whereas muscle activity of the biarticular muscles remained constant. This validates the assumption that both muscle groups have a different role to fulfil.

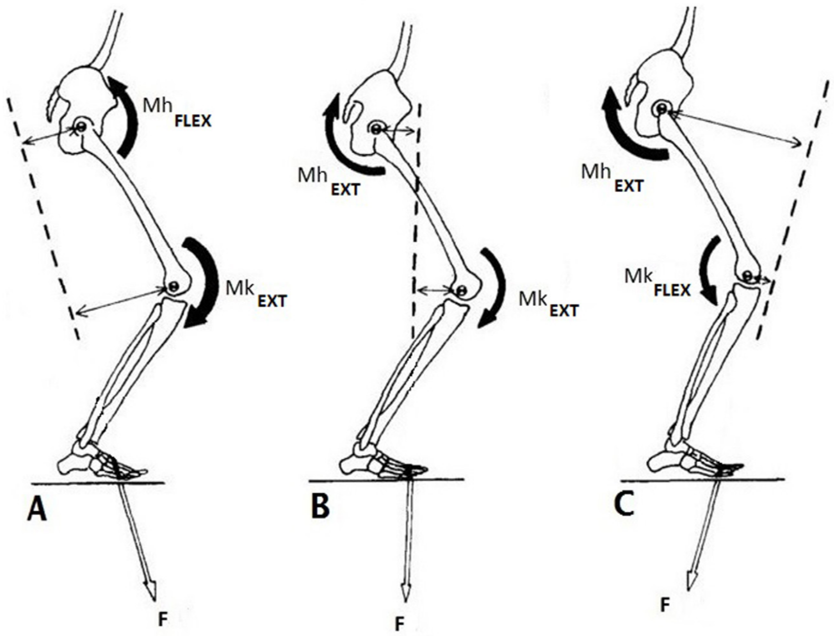

Figure 4. Required force direction and consequential joint torque for optimal power transfer on the pedal for different moments in the crank cycle. From left to right the situation in the first half of the down stroke, halfway the down stroke, at 90°, and in the second half of down stroke is shown. Subscript 'EXT' indicates an extension moment, 'FLEX' a flexion moment. Figure adapted from [60].

2.2.3. *Double joint actuation*

A third way for the biarticular muscles to contribute to energy efficiency of locomotion was recognised while analysing human running. While in jumping, biarticular muscles were active when the spanned joints displayed powers of the same sign, i.e. positive in the push-off phase and negative in the landing phase, Elftman [62] stated that biarticular muscles could also save energy in the phases of movement where powers at adjacent joints have opposite signs. In phases where negative joint power is seen at one joint, energy is being dissipated. If an adjacent joint is requiring positive powers at that time, it would be interesting to utilise the energy that would otherwise be dissipated at the other joint, to achieve this. Elftman also implied that, at such moments, one-joint agonistic and antagonistic muscles are not active, thus the power at adjacent joints is produced by biarticular muscles exclusively. During running, several phases of opposite power do occur. Elftman estimated that the economy of mechanical energy by biarticular muscles during running equals 47% of the total mechanical work of the joint moments [63]. However, in reality mono-articular muscles are active simultaneously with the biarticular ones: during certain phases in swing agonistic mono-articular muscles aid in the production of positive power and during stance antagonistic mono-articular muscles produce force simultaneously [64]. Therefore, Elftmans estimates of the energy saved by two-joint muscles are likely significantly higher than the actual values [63]. By including powers produced by mono-articular muscles in the calculation, Wells [65] obtained a considerably lower value: between 6 and 11%. Note that these boundary values were obtained by analysing vertical jumping and walking [63], respectively. This shows that double joint actuation is also performed in tasks other than running.

2.3. Critical view on past and present research

The three main functions that are attributed to biarticular muscles in literature are presented in the previous sections. In this section, the authors felt it important to also address the concern, expressed by some researchers, regarding biarticular muscles and their actual contribution to energy efficiency.

2.3.1. *Interpretation of simulation results*

A general remark; that is valid for all biomechanical and muscle coordination research, concerns the tools that are used. Because of the inability to measure all the necessary biomechanical quantities directly, hypotheses are usually tested/investigated with the help of simulation software. The traditional inverse dynamics method is commonly employed in locomotion analysis to compute net joint moments and net joint powers based on measured ground reaction forces and kinematics [30]. These joint moments are then used to drive the gait models. Although they are considered to be a good tool to provide a global insight in muscle function, Zajac *et al* [64] remark that they are likely not suitable to determine the function of an individual muscle due to their inability to account for co-activations. Gait models driven by individual muscles are believed to be critical to the understanding of the causal relationships between EMG patterns and gait kinematics and kinetics [64]. Muscle excitations are found by imposing certain constraints on the simulation [56]. In section 2.2.3, it was shown that end results can vary significantly based on a difference in initial assumptions. A different assumption made on mono-articular muscle activity, in an otherwise identical simulation, resulted in two different energy economy results, where one was approximately 4 times larger than the other. A critical evaluation of simulation results is thus always required when trying to assess muscle function.

2.3.2. Direction of energy transfer

The benefit of biarticular muscles transferring energy from proximal to distal joints, during the push-off phase of jumping, was explained earlier. Additionally, energy transfer in the opposite direction was shown to improve shock absorption in the landing phase. However, the actual direction of transfer in both phases has been put into question. Hosoda *et al* [33] designed a jumping robot, driven by pneumatic artificial muscles, that duplicates human leg structure and function. The monopod has three joints and nine muscles [66], of which three are biarticular. While, in one of the tests, Hosoda *et al* did confirm the energy flow as explained above from hip to ankle, they also managed to successfully perform a jumping motion driven by the knee extensors. In the latter case, the VAS muscle is extending the knee and HAM and GAS are transferring part of that power to hip and ankle joint, respectively, extending the entire leg [33]. A simulation performed by Pandy *et al* [51] reveals that in human jumping, it is most likely a combination of both approaches that is used to maximise jumping performance. GMAX and VAS were both determined to be the major contributors to the instantaneous power of the trunk, which suggests that energy flow is not exclusively directed towards distal joint. This was confirmed by Voronov, who identified a flow of power from hip to knee through the RF muscle, but also one from knee to hip via the HAM [48]. Similarly, Prilutsky *et al* [23] identified a flow of energy from hip to knee in the landing phase of jumping, in addition to the distal to proximal flow. Biarticular muscles are thus likely responsible for transfer of energy between joints in both directions in both phases. More research is required to investigate how exactly the complex flow patterns of energy between joints contribute to locomotion economy.

2.3.3. Transfer of energy between joints by biarticular muscles

Zajac *et al* [30] stated that the concept of transfer of power from one spanned joint to the other by biarticular muscles alone, is an explanation that is too narrow. He believes it has developed from the anatomical classification, in which muscles act to accelerate the joints they span [27]. Although this is a valid approach for a single joint system, it no longer applies to multi-joint systems, where no joint can be considered in isolation [59]. The contribution of a muscle's force on body motion can be found by applying mechanics to determine the direct multi-joint dynamics. Zajac *et al* [67] illustrate the difference between the dynamics of single-joint and multi-joint movements by comparing two simple models of standing: one where knee and hip joints are locked by external braces (one joint system) and another where the knee is allowed to bend (two-joint system). While acceleration of the segment (thigh and shank) in the one joint system is solely dependent on the muscles around the ankle, a dynamic coupling exists across all segments for the two-joint system. A concrete example: SOL acts to accelerate the ankle, the joint it spans, into extension. Yet, in flat-footed standing near the vertical posture (figure 5), it also acts to accelerate the knee into extension twice as much as the ankle because the thigh is accelerated into extension as much as the shank [67]. The dynamical interactions allow the muscle to influence the mechanical energy of segments it does not span. Because SOL is a mono-articular muscle, energy transfer is clearly not a *unique* function of biarticular muscles. Thus, every muscle can cause a redistribution of mechanical energy among the body segments during task execution [42, 56]. This claim was already made earlier by Pandy *et al* [51], while analysing the role of the GAS muscle in jumping. He argued that although GAS did significantly contribute to jumping performance, its biarticular nature was not crucial [51]. This was demonstrated by replacing the GAS muscle by a structurally identical mono-articular ankle extensor in their dynamical model [68]. Without the presence of the biarticular GAS, jumping performance did not decrease at all, but even slightly increased [51].

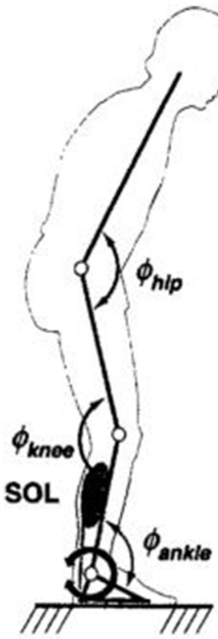

Figure 5. Flat-footed standing near the vertical posture. The Soleus acts to accelerate the thigh clockwise as much as it acts to accelerate the shank counter-clockwise. The knee is thus extended twice as much by both phenomena than the ankle by shank acceleration alone [27].

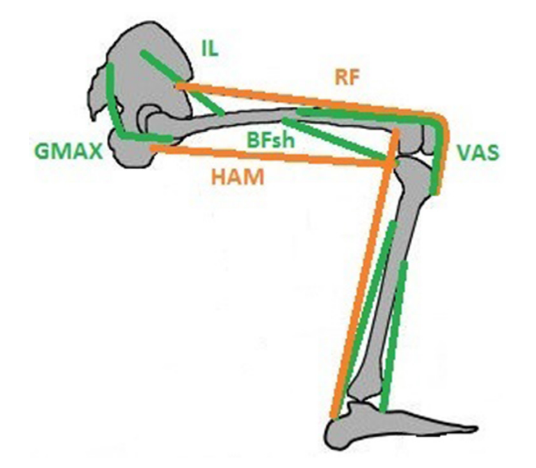

Figure 6. Lower limb model. Figure adapted from [30].

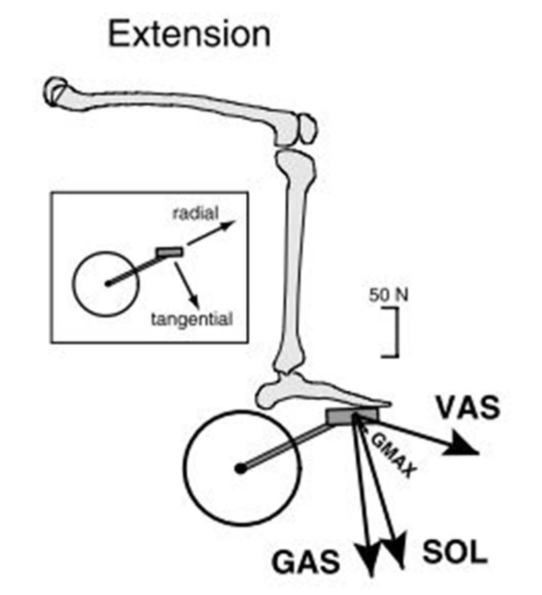

Figure 7. Representation of the instantaneous force direction and magnitude that individual muscles can exert on the pedal during cycling [30].

These claims were countered by Van Ingen Schenau *et al* [43], stating that use of the expression 'transport of energy' in two different definitions has led to some confusion. Authors such as Pandy [69] and Zajac *et al* [67] define transport of energy as the flow of energy between all the segments of the lower limbs calculated by use of the joint moments and (external) joint forces. A detailed explanation of the calculation of these segmental energy flows can be found in [30]. Van Ingen Schenau *et al* [43] emphasize that the transport of energy, as discussed in their publication, has nothing to do with these flows of energy between segments. What is meant in their publication is based on an instantaneous power equation of the system that does not contain the joint forces. A simple example was given to illustrate this: consider the model given in figure 6, consisting of a set of mono- and biarticular muscles. Imagine that GMAX and VAS are both creating a moment around the hip and knee joint, respectively, thus extending the leg. If RF is activated so that its length is kept constant, the net moment in the hip decreases and the net moment in the knee increases. If, for the sake of simplicity, extension velocities of the joints remain the same it is easy to see that net hip power decreases as a result of RF activation and net knee power increases. This redistribution of torque, and consequently of joint power, is described as 'transfer of power between joints by a biarticular muscle'. A more detailed explanation can be found in [70].

Zajac *et al* [30] responded by recognising the confusion concerning the phrase 'transfer of power from one joint to another by a biarticular muscle' and accepting that this phrase was not used to infer how the net joint moments transfer power among segments. They also acknowledge that biarticular muscles do display the unique property of producing moments simultaneously at the two spanned joints and therefore might be advantageous to the execution of a locomotion task. To clearly indicate the difference between the approaches of Zajac and Van Ingen Schenau, the authors suggest to use another name for the unique action of biarticular muscles as defined in section 2.2.1. 'Coupling of joint movements' is an expression that covers the action of the biarticular muscles as identified in jumping and was previously also used by Van Ingen Schenau *et al* [43]. Additionally, Zajac *et al* do not exclude the possibility that biarticular muscles might cause energy to be exchanged among the segments in a manner unachievable by the action of any *single* mono-articular muscle due to this coupling of joints. However, this needs to be further analysed.

2.3.4. Controlling force direction

Kuo [59] pointed out that the efficiency advantage in controlling the force direction simply depends on the availability of a muscle whose output force direction at the end-effector, i.e. the direction of the force exerted onto the pedal, is more closely aligned to the angular velocity vector than that of another muscle. Although biarticular muscles are capable of achieving this, a mono-articular muscle can also function in this capacity. Zajac *et al* [30] clarified this by displaying the instantaneous force directions and magnitude of several lower limb muscles in pedalling, as shown in figure 7. Although literature has shown that the mono-articular hip (GMAX) and knee extensors (VAS) are the main power providers in cycling, the direction of the force they can supply on the pedal is anything but optimal. On the other hand, the SOL and GAS do not provide a high work output, even though their output force direction is quasi parallel with the direction of motion. Because of the low mass of the foot, if no other muscles were generating force, the hip extensors would act to accelerate the foot quickly into dorsiflexion and no tangential crank force would be developed. Instead, the plantar flexor muscles stiffen the ankle to prevent it from collapsing and the energy produced by the hip extensors can be delivered to the crank. The fact

Table 1. Human locomotion is characterised by specific dynamics, robustness to changes in the environment and efficient use of energy. Biarticular elements were suggested to allow the implementation of all of these properties in bipedal robot locomotion. Each of the references describes how biarticulars contribute to the achievement of these properties.

Property:	Human dynamics	Robustness	Energy efficiency
	Dean *et al* [74]	Iida *et al* [77]	Lahr *et al* [72]
	Seyfarth *et al* [78]	Scholz *et al* [79]	Lahr *et al* [80]
	Iida *et al* [77]	Hosoda *et al* [33]	
	Sharbafi *et al* [81]	Sharbafi *et al* [81]	
	Asano *et al* [82, 83]		

that GAS is a biarticular muscle is not crucial here, as a simulation without it can also perfectly replicate the measured kinematics and kinetics as long as SOL excitation is increased proportionally [30, 56].

2.4. Conclusion

The biomechanical review presented in this section explained how biarticular muscles contribute to energy efficiency in locomotion. Three separate mechanisms have been identified by which this is achieved, i.e. joint motion coupling, efficient orientation of output force and double joint actuation. The discussion presented in section 2.3, clearly shows that the basic principles behind biarticular muscles are not completely uncovered yet. Although the contribution of these muscles to locomotion economy, following the mechanisms described earlier, is not denied, some researchers do believe that it is not necessarily a *unique* quality of biarticular muscles. Mono-articular muscles have also shown to improve output force direction and to cause an exchange of energy between the body segments. However, it is generally accepted that biarticular muscles are unique in their capability of producing moments simultaneously at the two spanned joints. It was not excluded that this coupling of joints might contribute to locomotion economy in a way unachievable by mono-articular muscles. More research is required to determine the exact working principles behind that. Taking a closer look at the role of biarticular elements in robotic applications might help to shed some light on their unique qualities.

3. Biarticular elements in robotics

In the biomechanical section of this work, biarticular muscles were identified as the tools that decrease energy consumption during locomotion. Some discord exists among researchers on whether a muscle need to be biarticular in order to achieve this. This section gives an overview of the application of biarticular elements in bio-inspired robotics. First, this section discusses the role of biarticular elements in making robotic bipedal gait more human-like. After that, the application of multi-articular elements as joint couplers, output force controllers and double joint actuators, thus mimicking the function of biarticular muscles, is investigated by looking at exoskeletons, robotic manipulators and prostheses. Lastly, this overview was used to evaluate the need of multi-articularity in the discussed applications.

3.1. Human-like bipedal robot locomotion

Bipedal robots can navigate the same environment humans do by walking among and over obstacles and climbing stairs. Yet, they often operate with low energetic efficiency and unnatural gaits [71]. To be useful as a tool, humanoid robots demand a large-scale improvement in energy storage and efficiency technology [72]. Human locomotion is characterised by a specific pattern of motions and muscle actions to support body-weight and maintain dynamic stability during progression [73, 74]. These induce very robust, versatile and energy efficient functional abilities in a vast range of locomotion conditions [75]. In order to capture the basic dynamics of walking, Geyer *et al* [76] showed that compliant leg behaviour is crucial. Torricelli *et al* [75] suggested the implementation of biarticular elastic elements as a tool to capture the natural dynamics of human walking, introduce robustness to different terrains, and lower energetic costs. These three different properties, that are inherent to human gait, have been listed in table 1. The references, that are shown under each property, explain how biarticular elements allow to achieving this. Each of these will now be discussed in more detail.

3.1.1. Human dynamics

Often, the likeness of robot and human locomotion is assessed by analysing ground reaction force (GRF) patterns [84]. However, for simple passive dynamic walkers, a comparison is often done based on more global parameters such as gait speed, relative length of the stance/swing phase, step frequency, joint kinematics and so on. Dean *et al* [74] observed that although the passive dynamics of bipedal limbs alone are sufficient to produce a walking motion, robots using passive dynamics walk much slower than humans. While a relaxed human generally walks at around 1.25 $m\ s^{-1}$, dynamic walking machines are limited to one-third of that. In order to increase the walking speed of dynamic walking models, Dean *et al* added elastic elements to two kneed dynamic walkers. One was equipped with antagonistic hip and knee springs. In the other hip and knee springs were combined into two biarticular ones, spanning both joints. Although he succeeded in achieving typical human speeds in the mono-articular model, he found that the model always walked with either poor economy and/or foot scuff. The biarticular model allowed him to achieve the same speeds, yet provided him with the possibility of modulating step length and frequency in order to ensure proper foot clearance without compromising economy. A comparison with human gait showed that the biarticular model displayed close resemblance to human kinematics whereas the mono-articular model did not. Seyfarth *et al* [78] were able to achieve similar results in a simulation study for running robots. At high speeds, they were also able to find a human-like transition from walking to running. Both results were also identified in experiments that were executed with a bipedal robot.

Although the research presented above indicates that biarticular elements might be crucial in attaining human-like speeds and leg kinematics, it deserves to be noted that this indication is based on the study of dynamic walkers that utilise elastic elements. Human muscles consist of an additional active component in parallel to their compliant behaviour [16]. Therefore, a bipedal walker actuated by mono-articular muscles would be more versatile than one that is solely dependent on passive elastic elements because it can rely on motors to actively power locomotion or adapt joint stiffness as required. Although the authors have not found a confirming study in literature, it is possible that a bipedal walker, equipped with well-controlled mono-articular actuators, is capable of replicating human walking dynamics without the addition of biarticular elements. However, other criteria have led researchers to choose for the implementation of biarticular elements in parallel with mono-articular actuators [81, 85, 86]. The cited works are realised as a part of the BioBiped project, where the goal is to investigate and realize human-like, stable locomotion in humanoid robots. In [85, 86], passive elastic biarticular elements were added to a bipedal robot of which the joints are actuated by mono-articular series elastic actuators. Although human-like GRF patterns were observed with the mono-articular design in a jumping experiment, Radkhah *et al* [86] discovered that the addition of a biarticular GAS structure smooths the vertical GRF patterns, and increases both ground clearance and flight phase duration compared to the mono-articular set-up. Additionally, they observed a decrease in ankle energy consumption and suggested that a careful optimisation of the biarticular structure, which was not done in their study, could further enhance energy savings of both the ankle and the knee. Similarly, in a walking study, Sharbafi *et al* [81] were able to reproduce human-like swing leg dynamics, which is reflected in the shape of the GRFs, by utilising a biarticular HAM and RF series elastic actuator. This can be achieved fully passively, as all series elastic actuators were locked during the swing phase, thus operating as passive elastic springs [81]. In [87], the role of biarticular elements in leg swing reproduction is extensively discussed and a detailed comparison is made with human walking. The BioBiped studies confirm that biarticular elements could be important to generate human-like walking because they allow to mimic human dynamics, while also contributing to other aspects that are characteristic for human locomotion such as energy economy.

The humanoid robots that were cited so far, are designed to reproduce simplified human locomotion in the sagittal plane. However, in reality, human locomotion is three-dimensional in nature [88] so in order to truly capture human dynamics, more complex robots are required. Research of Inaba *et al* into musculoskeletal robots has uncovered the use of biarticular elements in achieving this. In the robot Kenshiro, biarticular actuators were added to the musculoskeletal design [89]. The robot also includes a knee internal/external rotation DOF, which is actuated by the biarticular hamstring muscle actuators as seen in humans [82, 83]. One of the hamstring actuators (representing the Biceps Femoris muscle) is responsible for external rotation, while the other (representing the Semimembranosus and Semitendinosus) is responsible for internal rotation. Clearly, human muscles are not solely active in one plane, although they are often modelled as such. Biarticular actuators in a humanoid design can thus allow out-of-plane movements of the knee, without the need for additional actuators.

3.1.2. *Robust gait*

In [77], Iida *et al* presented a minimalistic bipedal robot with compliant legs that utilises a biarticular arrangement of tension springs. Again, the implementation of biarticular elements resulted in more human-like joint kinematics, for walking and running velocities. Additionally, they were also able to conclude that the coupling between joints increased the stability of locomotion, thus making it more robust to environmental perturbations. Similarly, Scholz *et al* [79] reported that simulations and experimental tests with the humanoid robot BioBiped2 showed a significant improvement of synchronised joint movement by use of an elastic GAS-mimicking structure. The synchronisation of the knee and ankle movements was quantified by calculating the phase difference between the flexion-extension motions of these two joints. Although synchronised joint movement was possible without the biarticular element, the operating region was very limited. With the implementation of the biarticular element, the phase difference was reduced for every leg configuration tested on the robot, drastically increasing the operating region. Scholz *et al* [79] concluded their work by remarking that for robots in real world scenarios, variations in leg configurations are inevitable. The additional robustness, gained through the addition of the biarticular structure, against changes in leg configuration could help in

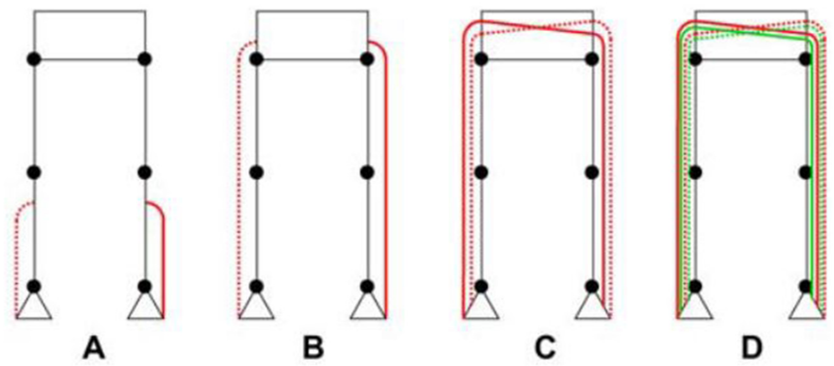

Figure 8. Frontal view of the different exotendon configurations that were investigated by van den Bogert [37]. Continuous and dashed lines of the same color represent symmetric tendons with the same design parameters. The tendons only provide torques around the joints in the saggital plane, i.e. flexion of extension. Figure was taken from [37] (Licensed under a Public License and available at: www.biomedical-engineering-online.com/content/2/1/17).

solving the challenges of bipedal walking on rough terrain and in unstructured environments. The work of Hosoda *et al* [33, 66] with humanoid robots, driven by pneumatic artificial muscles, reflects this in the design of their controller. While joints can be explicitly coordinated by the controller in robots that are actuated by antagonistic pairs of mono-articular pneumatic muscles [66], the control scheme can be significantly simplified by adding biarticular muscles [33]. Hosoda postulated that stable motion can be realised without high-bandwidth control if the compliance and joint coordination of the muscular-skeletal system is utilised. Several jumping experiments proved that joint coordination can in fact be realised by changing the tension in the biarticular muscles [33]. Sharbafi *et al* came to the same conclusion in their experiments with the jumping robot BioBiped3 [81].

3.1.3. *Energy efficiency*

Lahr *et al* [72] introduced biarticular elements as a possible means of improving energy efficiency of humanoid robots. A genetic algorithm was used to find the most efficient configuration for walking and standing up. The results showed a dramatic improvement in efficiency of up to 30% compared to the reference situation where no biarticular elements were implemented. Interestingly, although the implementation of biarticular elements was inspired by the biological muscle architecture of humans, the majority of energy savings can be traced to a non-biological coupling: i.e. between the hip abduction axis and the knee flexion axis. This was explained by stating that although humans and humanoids are similar, other constraints ensure that robots are still merely inspired by humans, and cannot be direct copies [80].

3.2. Mimicking of biarticular muscle functions

3.2.1. *Energy transfer/joint coupling*

In the experiments that were discussed in the section 2.2.1, to demonstrate the ‘energy transfer/joint coupling’ function, the biarticular muscles are represented by a non-stretchable element. This tendon-action of biarticular muscles, where the muscle does not change length, could be performed by passive elements, making it an energy economic solution. This section will describe the theoretical benefit of passive tendons spanning multiple joints in an exoskeleton for walking, as well as an experimental validation. The comparison of both reveals an important disadvantage of passive elements with regards to exoskeleton versatility. The section will then continue by reviewing several devices that employ active multi-articular elements to couple joint movements. In the latter discussion, the severity of the influence of added mass and inertia on the wearer of an exoskeleton is highlighted.

Passive joint coupling

In a simulation study, van den Bogert [37] showed that passive exotendons could significantly reduce the muscle forces required for locomotion. He investigated four different exotendon configurations, which are shown in figure 8. Only configuration A is based on a biological counterpart, i.e. the SOL muscle. The others show a coupling between the joints that is different from the biological one: a tendon crossing all three joints in one leg (B), a tendon crossing all six lower limb joints, thus linking both legs (C), and two six-joint tendons (D), each with their symmetric counterpart. After optimisation of the tendon parameters, configuration A was able to reduce the muscle joint moments by 21%, configurations B and C by 46% and D by 71%. Under the assumption that a reduction in required muscle activation also leads to a reduction in energy expenditure [9], the exotendon strategy proposed by van den Bogert appears to be promising.

In 2011, Van Dijk *et al* [90] performed experimental trials with an exoskeleton that was constructed according to one of the exotendon designs described by van den Bogert. They chose to experimentally validate configuration B, where an artificial tendon spans the ankle, knee and hip of each of the legs. Although this was not the most promising configuration, it was chosen as a trade-off between efficiency and complexity [90]. Unfortunately, the experimental tests could not reproduce the results observed in the simulation [91]. In fact, the energy expenditure of all the trials with the exoskeleton was higher than that of the trials without the exoskeleton [90]. A remark made by the researchers at that point was that due to significant changes in the gait pattern, the expected supportive torques might have been considerably higher than what was actually transferred to the wearer [90]. This, in combination with the increased mass and inertia of the leg while wearing the exoskeleton, could certainly explain the noticed increase in energy expenditure.

To increase the versatility of the system, the incorporation of an active element, to adjust tendon length, is advised. This would allow for an adaptation to altered kinematics, thus increasing the exoskeleton's performance or the possibility of assisting other activities. A simulation performed by Prilutsky *et al* [23], on the execution of a squat jump, showed that biarticular muscles are actively powering the legs and are thus changing length as well. A conclusion that was supported by other researchers, based on their own research [51, 92].

Active joint coupling

Malcolm *et al* [91] designed an active exoskeleton mimicking the GAS configuration by means of a pneumatic artificial muscle in series with an elastic element. The exoskeleton was tested in a configuration that mimics the eccentric-concentric behavior of the GAS and one that mimics the SOL behavior, by changing the top connection point from thigh to shank. Oxygen consumption for both was significantly smaller than that for the unpowered state (wearing the exoskeleton but not providing any assistance). The reduction of oxygen consumption due to the biarticular configuration is twice as big as that due to the mono-articular one: 13 and 6%, respectively. Yet, neither showed a significant reduction when compared to the unequipped reference state (not wearing an exoskeleton). This is in contrast to a previous study with the mono-articular version of the device, where a reduction of 6% was seen compared to the unequipped state [93]. The additional encumbrance of the thigh segment of the exoskeleton was mentioned as a possible reason for this effect. Although these results are providing a positive view on the use of biarticular actuators, exoskeleton mass and inertia is proving to be a serious problem [94, 95].

In the attempt of addressing this problem, Asbeck *et al* have looked into the use of soft exosuits as an alternative for the rigid (and heavy) structures that are usually utilised. The system, presented in [96], creates forces on the body during walking through a combination of passive and active tensioning. Passive tensioning is provided by the webbing and fabrics of the suit during motion, while active tensioning is provided by a Bowden cable. In figure 9, a recent version of the exosuit is shown, where the original blue force path is supplemented with a green one providing hip extension. The blue force path consists of webbing and a Bowden cable. The sheath of the Bowden cable is connected to the bottom of the webbing, while the inner cable extends further to the foot, which is clearly displayed in the schematic drawing. When the actuators retract the inner cable, tension is created in the exosuit, which subsequently creates moments about the ankle and hip joints through the suits architecture. As such, the hip joint and ankle joint are coupled. Preliminary experiments with the original suit, i.e. no hip extension actuation, have shown a gross metabolic benefit of 6.4% when the exosuit was turned on, compared to a trial where it was turned off [96]. Asbeck *et al* do indicate that the prototype served as a mere proof of concept and was not designed in order to minimise the mass of the device. The mass of the prototype can be greatly reduced by a redesign of the actuator units that are carried on the back. According to a calculation performed in the study [96], a reduction of the weight by approximately 50% would allow for the suit to reduce metabolic cost compared to the unequipped reference state. Redesign and optimisation of control of the soft exosuit has since shown a further increase in gross metabolic benefit between the powered and unpowered state (up until 23% in [98]). Despite modifications to the design, the connection between ankle and hip has been maintained in all the intermediate versions of the suit [97, 99, 100], indicating its utility. Unfortunately, no additional data was provided concerning the

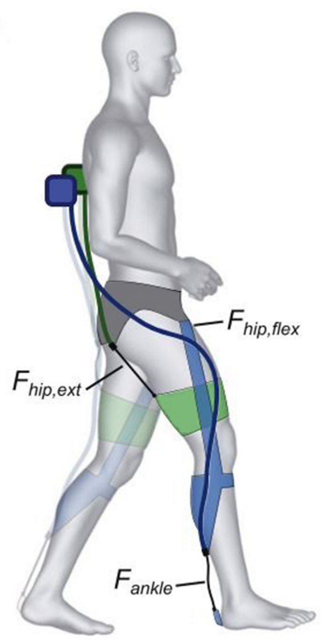

Figure 9. Schematic view of the exosuit, originally developed by Asbeck *et al* [96]. In blue, the multi-articular connection between ankle plantarflexion and hip flexion is shown. The hip extension actuation (green path) was later added by Panizzolo *et al* [97]. Figure was adapted from [97] (licensed under a Public License: https://creativecommons.org/licenses/by/4.0/).

metabolic benefit compared to an unequipped reference state.

Where, the exosuits described above have been predominantly used to enhance the activities of healthy users, Bartenbach *et al* [10] developed a suit for the assistance of people with gait and lower limb impairments due to medical conditions or age. More precisely, the suit is meant to assist its wearer during standing up and climbing stairs, as an encouragement to leave the wheelchair more frequently. A support for level walking was considered desirable but not necessary. Similar to the device of Asbeck *et al* [96], each leg of the suit is powered by means of a Bowden cable actuator. However, after careful evaluation, the coupling of knee and hip extension was seen to maximize the amount of work that can potentially be used to support the wearer during the selected motions, i.e. 78.4% of the biological work for standing up, 53.5% for climbing stairs and 10.7% for level walking. In a more recent version of the suit, the Bowden cable actuator was complemented with an antagonistic elastic tendon, which increases the stability of the exosuit and allows support of both flexion and extension [101]. The evaluation of the prototype is currently still ongoing and no experimental data is available yet. However, the researchers do indicate that they expect a significant improvement of user mobility, as well as a positive impact on the neuromusculoskeletal system by exploiting joint synergies [101].

3.2.2. *Efficient control of output force direction*

Biarticular muscles are also thought to play a role in the efficient control of output force direction. BiWi [102] is a two-joint, bio-inspired manipulator that is actuated by two sets of antagonistic mono-articular actuators, i.e. one set at each joint, and two biarticular ones. The actuator set-up is schematically depicted in figure 10. This bio-inspired approach is proposed so the manipulator can produce a human-like force at the end effector (E). Experiments have shown that the proposed manipulator can produce a homogeneous maximum force at the end effector [103] with a hexagonal shape as human arms can do [104]. These advantages are directly attributed to the biarticular actuators, which are present as a redundancy in the actuation system [102, 105, 106]. Drawbacks of this design are added complexity, mass and cost. In [103], Salvucci *et al* investigated the role of biarticular actuators for a robot arm equipped with as many actuators as joints. Hence, there is no more actuator redundancy. A comparison of end-effector force sizes and directions was made between two actuator configurations: one consisting of two mono-articular actuators, i.e. e1–f1 and e2–f2 (figure 10), and another consisting of one mono-articular actuator and one biarticular actuator, i.e. e1–f1 and e3–f3 (figure 10). Experimental trials showed that even in a non-redundant set-up, the manipulator with biarticular actuator resulted in a more homogeneous maximum force output. Salvucci *et al* concluded that in dynamic conditions, this would result in a greater capability of disturbance rejection to forces directed horizontally with respect to the ground for walking robots [103]. As a consequence, the presence of biarticular actuators improves the balance capability of walking robots.

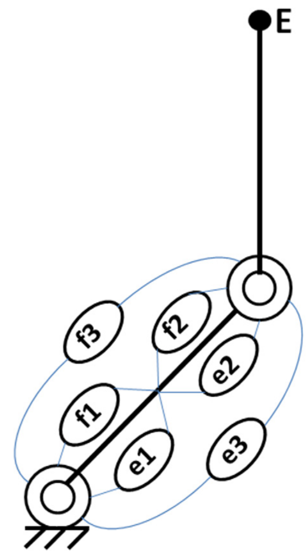

Figure 10. Schematic of a robotic arm with two pairs of mono-articular antagonists, e1–f1 and e2–f2, and one pair of biarticular antagonists, e3–f3.

So far, the research presented in this section revealed that biarticular actuator set-ups are more suited to produce human-like end-effector patterns. On the contrary, nothing has been said about the efficiency in which they achieve this. A study concerning the efficient force transmission by biarticular actuators was performed by Oh *et al* [107]. In this work, the two actuator configurations previously discussed by Salvucci *et al* [103] were compared. Each muscle-structure of the robot consists of an identical geared servomotor, whose output torque is transmitted to the joints through a pulley and wire system. For both actuator configurations, the motor torques required to perform a circular force pattern at the end-effector E (as required in pedalling) were compared. Motor torques were significantly bigger in the mono-articular configuration then in the biarticular one. Although no explicit energy consumption calculation was performed, Oh *et al* [107] concluded that this shows a more efficient control of end-effector force direction when biarticular actuators are used, compared to the mono-articular configuration. Note that while energy economy in humans is obtained by preventing dissipation of energy due to eccentric contractions, in the robot arm it is obtained by a more efficient distribution of torque over the joints. An action that, in this particular case, can only be performed by elements spanning multiple joints. Because in this work, identical geared servomotors were used the results described here need to be handled with care. It is possible that by altering the motor selection or gear ratio for different

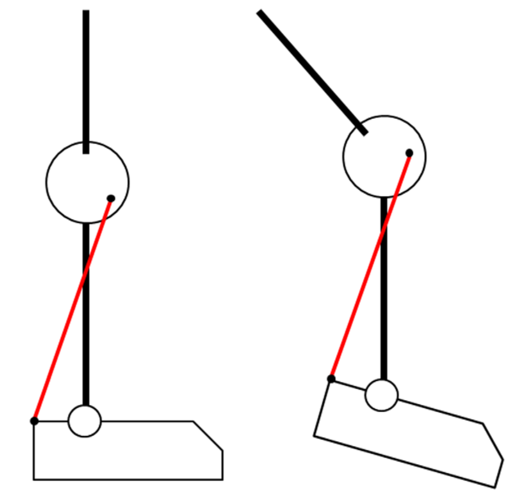

Figure 11. Schematic view of connection for double joint actuation during the pre-swing phase of gait. The biarticular tendon (red) simultaneously provides negative power at the knee, preventing knee collapsing, and positive power at the ankle, driving push-off.

joints, the cost-benefit equation changes and biarticular elements are no longer the better choice. Additional research is required to investigate this.

Niiyama *et al* [46] utilised the maximum end-effector force output strategy, as used by all the research cited in this section, as a method to design a bio-inspired, jumping robot. Maximum output force profiles of the robot were calculated for three different muscle configurations: an anthropomorphic configuration (including GMAX, IL, HAM, RF, VAS, GAS, SOL and TA), a uniform configuration (consisting of all the former and a biarticular antagonist for GAS), and a mono-articular configuration (consisting of a pair of mono-articular antagonists at hip, knee and ankle). For each of the configurations, the total amount of muscle force, i.e. sum of the maximum forces of all the muscles in the design, was kept constant. This, to avoid a negative bias for the mono-articular configuration, which has less muscle elements than the other two (6 compared to 8 and 9). The anthropomorphic configuration exhibited a force profile with considerably larger downward forces than the other configurations. As such, the maximum end-effector force output strategy suggests the anthropomorphic configuration as the better option for achieving a maximum jumping height.

Similarly, the force output approach explains why the presence of biarticular elements improves robot stability, as already claimed by Salvucci *et al* [103] earlier in this section. In a modelling study, Hof [108] defined the output force direction due to the action of individual muscles when the leg is almost straight. Where the action lines of mono-articular muscles are all directed lengthwise along the limbs, those of biarticular muscles can have a strong transverse component. Because perpendicular leg forces are generally associated with postural control [81], it is easy to see the advantage of biarticular muscles over mono-articular ones. Tests performed on humans confirm that, in perturbed standing, it are the biarticular muscles that display increased EMG activity [81]. In a standing test with BioBiped3, Sharbafi *et al* [81] compared the performance of the mono-articular actuators with that of the biarticular actuators for redirecting the GRF in a (static) standing position. GRF control by mono-articular actuators displayed larger errors and more oscillations than that by biarticular actuators. Achieving similar performance was only possible at the expense of higher control effort and larger sensor and actuator bandwidth. Additionally, Sharbafi *et al* [81] also observed that mono-articular postural control displayed inefficient use of injected energy. Because the activation of mono-articular muscles results in significant output forces along the leg [108], an increase of energy expended by the knee actuator was observed to compensate for these forces and maintain the static condition [81]. This means that, similar to the human situation discussed in section 2.2.2, an increased energy input of one mono-articular actuator is required to cancel out the input of another. Thus, tests with the biped do not only confirm that postural control is simplified when biarticular elements are exploited, they also indicate that injected energy is more efficiently used compared to solely relying on mono-articular elements.

3.2.3. Double joint actuation

Although energy dissipation in muscles can be prevented in certain circumstances, as is the case with output force direction, in some situations a braking action of certain joints is required. During normal walking, the knee performs primarily negative work, dissipating around 13 J per step [109]. Mechanically speaking, absorbing the dissipated energy in that joint and using it to power another, i.e. double joint actuation, looks like an ideal way to reduce the energy consumption of a device.

Human gait is characterised by knee flexion during the weight acceptance phase thus requiring a braking torque to prevent the knee from buckling under the weight [110]. Between the end of the weight acceptance and the point of maximum knee flexion, i.e. in the pre-swing phase, a breaking torque is needed again, to prevent the knee joint from collapsing during the push-off phase [109]. The knee thus requires negative power while the ankle needs a positive power burst for push-off. This pre-swing phase of gait would thus be an excellent candidate for double joint actuation of ankle and knee, by an element connecting both as shown in figure 11. The biarticular tendon simultaneously provides the negative power required at the knee and positive power required at the ankle.

Double joint actuation has already been successfully applied in several passive transfemoral prostheses, where the power used to propel the ankle into push-off is obtained by harvesting energy that would

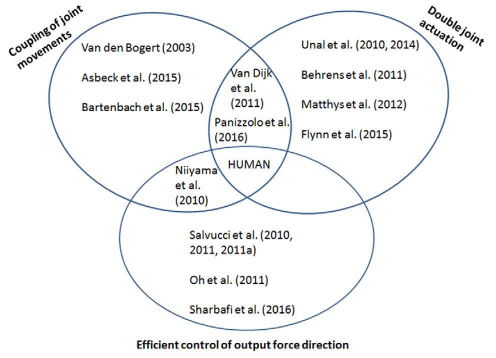

Figure 12. Visualisation of the classification of robotic applications of biarticular elements according to the functions displayed by those elements.

normally be dissipated [111, 112]. The prosthesis of Unal *et al* [112, 113], is partly powered by mimicking the Achilles tendon at the ankle: storing energy, that is normally dissipated by the ankle muscles, in a spring and using it to power ankle push-off. Apart from this, a biarticular element allows for double joint actuation during the pre-swing phase, as described above. Due to a difference in timing between ankle push-off and knee negative power zones, the amount of power that can be transferred like this is limited: only 0.09 J kg^{-1} of the required 0.35 J kg^{-1} for push-off [114]. This can be remedied however by use of a locking system, allowing for storage of another 0.11 J kg^{-1} [114] of energy from the knee in the biarticular element, that can be used for the subsequent ankle push-off. As such, the biarticular element continues actuating two joints, be it delayed. The prototype was experimentally validated on both healthy subjects and transfemoral amputees. The tests with healthy subjects were not conclusive due to a questionable attachment of the prosthesis to the user [114]. Results with an amputee showed that a significant amount of power was available for ankle push-off, resulting in more natural hip kinematics, which was seen as an improvement of gait and an indication of reducing the metabolic cost of the amputee during walking [114].

In the CYBERLEGs project [115], such a coupling between the ankle and the knee (as visualised in figure 11) is incorporated into an active transfemoral prosthesis. The prosthesis consists of a passive knee and an active ankle joint. The cable between both prevents the knee from collapsing during the push-off phase, while also aiding in ankle extension. A simulated reduction of energy usage of 30% was reported due to the coupling between both joints [109]. However, this value was not obtained in the experimental trials with amputees. Due to a lack of training time, several prosthesis parameter values had to be adapted during the test in order for the subjects to feel comfortable. Since the required cable length was determined on the parameters obtained from the simulation, the energy transfer mechanism was not operating optimally, reducing the amount of energy transferred from knee to ankle. In a next version of the prototype [116], a non-backdrivable trapezoidal screw drive was added to the energy-transfer mechanism, as a means to tension the cable at will, solving the problems experienced earlier. Although no energy consumption values were reported yet during the experimental trials of this new version, some subjects were able to increase their self-selected walking speed while using the prototype. This observation was used as an early indicator suggesting the utility of the components added to the device [116].

3.2.4. *Synthesis*

In the previous sections, robotic applications were arranged according to the primary function fulfilled by the biarticular elements. This arrangement can be visualised by means of a Venn diagram. The diagram shown in figure 12 consists of three sets, each representing one of the functions attributed to biarticular muscles. Ideally, all three functions are exploited to approach human performance. Although most robotic applications only fit in one of the individual sets, some of them display more than one of the functional properties of biarticular muscles and are situated in the intersection of multiple sets. In section 2.2.3 it was seen that joint coupling and double joint actuation are very similar, i.e. a distinction between both is made depending on the sign of the powers at the spanned joints. Therefore, it is not surprising that by incorporating biarticular elements into robotic applications often both functions are seen during operation. The work presented by Van Dijk *et al* [90], was earlier categorised under coupling of joint motion. However, after closer examination, the prototype also displays double joint actuation. In the last stages of stance, just before the onset of swing, the tendon simultaneously provides negative powers at the hip joint and positive powers at the ankle joint [90], similar to the double joint actuation exploited in prostheses design. Similarly, a recent version of the exosuit [97], that was originally developed by Asbeck *et al* [96], also displays a zone of double joint actuation before the onset of swing. It is clear from these examples that joint coupling and double joint actuation are closely related. The jumping robot by Niiyama *et al* [46] on the other hand, was designed by selecting the muscle configuration with the most optimal end-effector force output for the selected task. A human configuration, which is known to display coupling of joint movements during jumping, was favoured. This indicates that both functions contribute to optimal jumping performance.

3.3. Conclusion

As seen in the overview of robotics applications, provided in this section, biarticular elements have been used to make robotic locomotion more human-like and were implemented in several devices to mimic the function of biarticular muscles in the legs.

The necessity of biarticularity in order to perform these functions was earlier questioned in section 2.3. However, due to the fact that they span multiple joints, researchers did confirm that they might contribute to locomotion in a way unachievable for any mono-articular muscle.

In bipedal robots, the introduction of biarticular elastic elements allows to reach human-like progression speeds without compromising on energy economy or foot clearance as is the case when only mono-articular springs are used. Even in robots equipped with series elastic actuators, research showed that, by incorporating biarticular elements, GRF patterns and swing leg kinematics could be replicated in a way that reduces the energy consumption compared to mono-articular set-ups and joint movement coordination could be achieved with a significantly reduced control effort. In robotic manipulators, biarticular actuators allowed for a homogeneous output force and direction similar to humans, where one-joint actuator set-ups led to more directional force fields. The application of the force control theory on bipedal robots explains how this simplifies postural control and reduces the inefficient use of actuator energy input. Finally, it is clear that providing powers at two joints simultaneously, is not feasible with a single mono-articular element. Therefore, the coupling of joints and actuation of two joints by implementing biarticular elements can reduce the required number of actuators. Exosuit actuation strategies, based on both principles, have shown to successfully assist two joints with a single actuator. On the other hand, prostheses based on the double joint actuation principle have shown to provide ankle push-off without the presence of an ankle-actuator.

We can conclude from this discussion that in robotic applications, biarticular elements have induced certain beneficial properties, that are not as easily replicated by mono-articular alternatives. As such, it is safe to assume biarticular elements do have a certain value in bio-inspired robotics and, as an extension, likely also in human locomotion economy.

4. Possibilities to application in exoskeleton actuation

As seen in the introduction, the successful application of exoskeleton technology in rehabilitation centers and daily life situations is hindered by the influence of exoskeleton mass and inertia on energy consumption and natural kinematics of the user. An improvement of exoskeleton energy efficiency decreases the need for heavy batteries and over-dimensioned motor combinations, thus reducing the total mass of the device and possibly improving its performance on interaction with the wearer. Mimicking the contribution of biarticular muscles to energy economy in the actuator design of an exoskeleton could help to achieve this mass reduction and thus improve the performance in reducing user effort.

4.1. Coupling of joint motion

The application of biarticular elements as joint couplers in exoskeletons has been extensively addressed in section 3.2.1. Active joint coupling was preferred because it increases the versatility of the system and allows to adapt to unexpected changes in joint kinematics. Although experimental testing has shown promising results, exoskeleton mass and inertia is proving to be a big problem. The exploration of soft exosuits is one way of dealing with this, but also exploration of non-biological couplings can provide some relief. Coupling of hip and ankle, as done by Asbeck *et al* [96], allows for a more convenient distribution of exoskeleton mass if the actuators are located near the proximal joint. As such, the coupling of proximal with distal joints could allow for a metabolically efficient manipulation of exoskeleton leg inertia similar to the human muscle distribution.

4.2. Control of output force direction

Output force orientation was seen to be more human-like and less energy costly when biarticular elements were used. When searching to apply this mechanism in exoskeleton actuation systems, one should first take into account the specific nature of exoskeletons. Only in the case where the user is paraplegic does the exoskeleton need to provide full support and essentially operate as a walking robot, carrying its user around. Provided that safety of the user is guaranteed, actuation systems designed for walking robots or robotic manipulators can be a good start because they have made it possible to beneficially mimic certain properties that are characteristic for human gait. The most important of which is probably the increase of joint coordination and disturbance rejection capability with a significantly decreased need for complex high-bandwidth control strategies [76, 117, 118]. In cases where the user is still capable of using his/her muscles to some extent, the exoskeleton acts as a mere tool, closing the gap between its user's capabilities and the task requirements. Ideally, the user is in full control and thus responsible for directing the motion and coordinating joint motion, while the exoskeleton merely provides assistive torques.

4.3. Double joint actuation

For double joint actuation, the application in transfemoral prostheses has shown that a more energy efficient actuation system is possible when double joint actuation is utilised. Flynn *et al* [109] were capable of showing a reduction in energy consumption due to the link between knee and ankle and Unal *et al* [114] were able to supply ankle push-off and improve amputee gait with a fully passive device. It is clear that, from a mechanical point of view, capturing dissipated energy at one joint and using it to power another is an appealing strategy in terms of energy consumption. In prosthesis research, providing ankle push-off has additionally shown to reduce amputee metabolic consumption [119–121]. Simply extrapolating this beneficial effect to exoskeleton operation however, is not possible. Where prostheses operate in series with the human user, exoskeletons operate in parallel. The reported angle trajectories of both prostheses, that were discussed earlier, are different from natural kinematics. A meticulous study is thus required to investigate how this would affect the gait pattern in exoskeleton locomotion. Additionally, several researchers have already warned that due to a focus on mechanical efficiency, exoskeleton performance is often overestimated, leading to poor results with reducing metabolic cost [122, 123]. This observation was confirmed by Robertson *et al* [124], who stated that although mechanical and metabolic performance benefits can be achieved simultaneously, neither is likely to be optimal while the other persists. It is thus imperative to carefully investigate the effect of double joint actuation in exoskeletons on the metabolic consumption of the user.

5. Conclusion

Human locomotion is considered to be an energy efficient way of navigating an unpredictable environment. Biarticular muscles are seen as one of the important contributors to human locomotion economy. In section 2.2, the three different operating modes of biarticular muscles, as contributors to energy-efficiency, have been identified: joint coupling, efficient coordination of output force direction and double joint actuation. However, several researchers argue that these functions could also be performed by mono-articular muscles, indicating that they do not necessarily rely on the unique property of biarticularity. This discord concerning biarticular muscle function is thoroughly addressed in section 2.3. It is a given however, that only biarticular muscles can simultaneously produce torque/power at two joints and, as such, couple joint movements or function as a double joint actuator. Researchers do agree that this property might cause them to contribute to locomotion economy in a way unachievable by mono-articular muscles. Additional research is required to validate this statement by supplying biomechanical evidence. However, in the mean time, an analysis of the use of biarticular elements in bio-inspired robotics can already help to shed some light on the situation.

Biarticular elements have been used to make robot locomotion more human-like and to mimic the function of biarticular muscles in robotic applications. Although several of the achievements made in these robotic applications could also be realised with mono-articular alternatives, the use of biarticular elements did induce several additional benefits that could not be easily replicated with mono-articular alternatives. They have been seen to reduce energy consumption, control effort and the required number of actuators, depending on the specific application. Therefore, it is safe to assume that they beneficially contribute to bio-inspired robotics and, as an extension, likely also to human locomotion. Although the authors of this work have extensively reviewed the role of biarticular muscles in energy efficiency and the positive effects of mimicking this in robotic applications, other functions were also attributed to them in literature. References have been made towards them improving shock absorption capability [23], as quickly mentioned in section 2.2.1, and minimising muscle fatigue by lowering the required muscle forces [125, 126], among others. Due to the extent of the subject matter however, the authors have chosen to limit the scope of the paper to those functions that are directly related to the improvement of energy efficiency. This, in order to improve the clarity and limit the length of the document. The review of the other biarticular muscle functions and the benefit of their application in robotics would make for an interesting addition to this study.

Although biomechanical studies and bio-inspired applications provide some indication that biarticular elements contribute to the energy efficiency of locomotion (human or robotic), it is clear that our understanding of their operation is not mature yet. Both observations are an encouragement to invest in novel research concerning possible applications. In this work, some suggestions were already made towards applying biarticular elements in exoskeleton actuation, but the lack of understanding of their unique contribution makes it challenging to use them beneficially. Particularly because the interaction between an exoskeleton and its user is not well understood yet either, making it difficult to predict what the effect on the user will be [17]. The limited number of research groups that have actually succeeded in reducing the users effort while wearing an exoskeleton is proof of the complexity of this problem. Inducing beneficial metabolic effects is the result of a complex balance between providing sufficient assistance, at the right time, and adding too much mass to the wearer [96, 127, 128]. The addition of biarticular elements further complicates this balance.

The authors feel that biarticular elements will play a crucial role in the future of exoskeleton actuation, yet they want to emphasise that the aim should always be to benefit the user. A 'trial and error'-based design process, that is focusing on intermediate user feedback rather than mechanical performance, will be the key to discovering a successful actuation strategy.

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