\subsection\*{Biarticular Actuation}

%TODO: There is a new review paper on this subject, we may update this section

Despite the developments in recent years, a number of challenges need to be surmounted to achieve high metabolic cost reduction to assist people more economically. One of the remarkable challenges on designing an efficient exoskeleton is mass minimization\cite{41,44,45} and more importantly, minimizing distal masses \cite{45} has a significant effect on exoskeleton efficiency since adding any mass to the distal extremity will increase the metabolic cost of the locomotion \cite{45} and walking pattern \cite{44}. To address this challenge, using passive exoskeletons without any actuation and power supply module has been proposed; although the metabolic cost reduction is low, they are lightweight assistive devices\cite{42,46}. An alternative solution is using tethered exoskeletons in which any heavy component is grounded, and actuation is off-board\cite{40,47}. However, these tethered exoskeletons restrict the mobility of the exoskeleton, and experimental results have been limited to lab-based scenarios.\\

It has been proven that human bipedal movement is an economical locomotion \cite{1,48} for various terrains \cite{1,49} and long distances \cite{50}. It thus inspiration for designing efficient mobile exoskeletons not only to solve the distal mass and inertia problem but also to provide some additional advantages on the exoskeleton design such as lower power consumption. One of the main reasons for human bipedal locomotion efficiency is the presence of specific muscles, biarticular muscles \cite{51,52,53}, which have several unique and notable roles on human locomotion.\\

A human lower limb has more muscles than is needed to actuate each degree of freedom(DOF) \cite{53} which means that human lower extremity is redundantly actuated, consisting of monoarticular muscles, which is a type of muscles spanning a joint, and another type span two joints known as biarticular muscles. Although the biarticular muscles, i.e. muscles span two joints, are not necessary for performing movements, they have not been eliminated from the human muscular system during human musculoskeletal system evolution, indicating their advantage for human locomotion \cite{53}. Moreover, the motor control system selects certain muscles to accomplish specific tasks\cite{54}, and the metabolic power consumption is one of the main factors to select muscles to need to be activated among the muscles of desired degrees of freedom \cite{53}. The significance of the biarticular muscles in the energy economy of locomotion has been proven by several computational analyses\cite{55,56} studying biarticular muscle activation during movement.\\

The effect of biarticular muscles on locomotion and their benefits have been discussed in multiple studies \cite{51,53,57,63}. One of the key benefits of biarticular muscles is transporting energy from proximal to distal joints produced by monoarticular muscles \cite{51,58,59,60,61,62}; studies on jumping, which is a high power demanding task, revealed that power produced by monoarticular muscles at each joint is not sufficient to produce a high jump\cite{58}, and power transportation is necessary to meet the power requirement\cite{58}. Moreover, this proximal to distal power flow allows for the distribution of the muscles weight, resulting in lower leg inertia \cite{62} which inherently requires less energy to be actuated, leading to more economical locomotion\cite{62,53}. Elftman\cite{64} also claimed, by studying the running task, that presence of biarticular muscles can regenerate the negative work in phases of running in which adjacent joints have opposite power signs resulting in more economical movement \cite{65} which was confirmed by \cite{66} for walking and jumping as well. \\

Another central role of biarticular muscles is facilitating the coupling of joint movement \cite{53,57}; thereby allowing control of the distal joint. For instance, if two joints are coupled with a stiff biarticular muscle, displacement of a joint will cause the movement of another joint as well due to biarticular muscle origin movement\cite{57}. This phenomenon is called ligamentous action \cite{67} which permits the location of most of the monoarticular muscles away from the distal joint and indirectly control them\cite{57}; similar to the energy transportation feature of biarticular muscles, this characteristic of biarticular muscle leads to lower inertia leg \cite{57,67} which can decrease the metabolic cost of locomotion.\\

The third remarkable benefit of biarticular muscles is controlling output force direction, which enables to get optimal output power. It has been shown that while most of the work is generated by monoarticular muscles, their output force direction is not optimal\cite{53}. Biarticular muscles are responsible for controlling output force direction\cite{53}, which must align with velocity to reach maximum output power\cite{53}. It has also been proven that biarticular muscles have lower contraction velocity than monoarticular muscles \cite{57}, resulting in the muscles having concurrent movements \cite{68}, and therefore higher muscle force compared to uniarticular muscles\cite{53}. \\

Biarticular muscle effect on limb stiffness has been studied by several researchers\cite{69,70}; one of the key findings is that loss of stiffness produced by biarticular muscles cannot be compensated by monoarticular muscle stiffness\cite{69,70}. These studies revealed that the presence of multi-joint muscles would dramatically increase the central nervous system ability to modulate endpoint stiffness \cite{70,71}. Additionally, biarticular muscle provides necessary coupling to regulate inter-limb interaction\cite{72}, and the absence of them would lead to elongated stiffness ellipse, reduce maximum achievable stiffness, and finally limit orientation range\cite{69}.

The stability effect of biarticular muscles is another role that has been studied \cite{73,74,76}. J. McIntyre et al. \cite{73} proved that the presence of biarticular muscles is necessary to provide a coupling enabling passive control of neuro-musculoskeletal system stability.\\

Considering all these advantages and roles of biarticular muscles in human locomotion, it has inspired the robotics field researchers to adapt their designs to take advantage of biarticular biological features\cite{53}. Several actuators \cite{77,78}, bipedal robots\cite{74,75,76} ,and assistive devices\cite{53} have been designed based on multi-articular muscles configuration.

The biarticular component has been used in designing several prostheses trying to mimic gastrocnemius muscle to reduce the actuators power consumption\cite{82,83,84,86,87} where results represent a promising improvement on the efficiency of prostheses\cite{87}. Several exoskeletons and exosuits are developed also to assist two joints simultaneously\cite{43,47,49,79,80,81}. Asbeck et al\cite{47} developed a soft exosuit assisting hip and ankle joints using the multi-articular concept on their design and reported 21\% to 19\% nominal metabolic cost reduction. Another noteworthy soft biarticular exosuit that has been designed for after stroke rehabilitation shows 32\% metabolic cost reduction\cite{43}. Quinlivan et al. \cite{80} developed tethered multi-articular soft exosuit, which demonstrated 23\% of metabolic burden reduction relative to powered of condition on healthy subject walking. Recently, Xiong et al. \cite{88} proposed a multi-articular passive exoskeleton assisting hip and knee inspired by power transportation feature of biarticular muscles where it stores negative mechanical work of knee joint and uses to assist hip extension, they succeeded to reduce the metabolic energy consumption by 7.6\% without using any actuation module.\\