

Recent Developments in Above-Knee Prosthetics and the Importance of Energy Recovery in Transfemoral Amputee Gait

Hande Argunsah Bayram^{1,2,3,4}

¹Acıbadem Üniversitesi, Mühendislik Fakültesi, İstanbul, Türkiye

²Kessler Foundation, Human Performance and Engineering, New Jersey, USA

³Cleveland Clinic, Biomedical Engineering, Ohio, USA

⁴Children's Specialized Hospital, Department of Research, New Jersey, USA

ABSTRACT

Objectives: Use of a spring as an energy harvest/release mechanism for transfemoral prosthetics designs is gaining traction. While springs theoretically can minimize the energy flow deficiency during the stance phase knee flexion, there are problems associated with controlling the release of energy harvested by springs.

The purpose of this review is to discuss the importance of controlled energy flow at the knee joint, recent attempts to harvest/return energy and the emphasis on the role of the ankle prosthesis in achieving assisted gait.

Study Design: Literature Review

Methods: Use of a spring in emerging prosthetic knee designs are presented in terms of their energy regeneration abilities along with their advantages and limitations.

Results: Use of a spring in knee prosthetics can cut power demand significantly as they mimic the musculotendonous structures by harvesting and returning needed energy.

Conclusions: Controlled energy flow at the knee joint could not only provide natural movement of the amputated limb but could also create positive power peaks at the knee joint. These features cannot be produced by any of the current generation of controlled damping prosthetic knees.

Key words: prostheses and Implants, knee, energy flow, spring

DİZÜSTÜ PROTEZ CİHAZLARDAKİ SON GELİŞMELER VE DİZÜSTÜ AMPUTE HAREKETİNDE ENERJİ GERİ DÖNÜŞÜMÜNÜN ÖNEMİ

ÖZET

Amaç: Diz üstü protezlerde enerji depolama ve geri dönüşümünde yay kullanımı sıkça kullanılan bir metod haline gelmiştir. Teorik olarak yaylar hareketin ağırlığı kabul etme döneminde gerçekleşen dizdeki bükülme süresinde enerji akışındaki kaybı azaltırken, sıkıştırılan yayın salınmasının kontrolünde bazı problemler mevcuttur.

Bu derlemenin amacı diz eklemindeki kontrollü enerji akışının önemini vurgulamak, son dönemde bu amaca ulaşmak için tasarlanan protezlerden bahsetmek ve bilek eklemi protezlerinin kontrollü ampute yürüyüşünü sağlamadaki önem ve katkılarından bahsetmektir.

Çalışma Planı: Derleme

Yöntemler: Hareket sırasında enerji geri dönüşümünü sağlamak amacıyla üretilen son teknoloji protez cihazlardan bahsedilmiş ve onların avantajları/eksiklikleri belirtilmiştir.

Bulgular: Yaylar kas ve tendon yapılarını taklit ederek hareket sırasında gerekli olan enerjiyi depolama ve geri gönderme sağlarlar, bu da güç gereksiniminin ciddi bir şekilde azalmasını sağlar.

Sonuç: Diz ekleminde kontrollü enerji akışı, ampute edilmiş bacakla normal harekete ulaşılmasını sağlamakla kalmaz, aynı zamanda dizde pozitif güç periyotlarının oluşmasını da sağlar. Bu kazanımlar, günümüzde var olan ticari protez bacakların hiçbirinde bulunmamaktadır.

Anahtar sözcükler: protez ve implantlar, diz, enerji akışı, yay

Above knee amputations occur for a variety of reasons such as disease, tumor, trauma, infection, or failed knee replacements. According to the National Limb Loss Information Center's statistics, in 2007 amputations due to vascular disease accounted for the majority (82 percent) of limb loss discharges. This rate increased from 38.30 per 100,000 people in 1988 to 46.19 per 100,000 people in 1996. War related trauma and accidents constitute the remaining 18 percent (1). It has been reported that 266,465 people had a transfemoral amputation between 1988 and 1996 and more than 80 percent of the amputations were due to diabetes. This is described as a new epidemic, with the number of diagnosed adults tripling between 1980 and 2005. According to statistics, one third of Americans are expected to be diabetic by 2050 (2-4). Without effective intervention of the growth of diabetes and treatment of its complications, this number has an unfortunately high potential of future growth. The prevention of death from diabetic complications may result in more amputees eventually experiencing serious, non-fatal consequences; making them even more sedentary via inadequate prostheses use. This not only reduces their quality of life but also accelerates other metabolic and cardiovascular problems.

Besides the emotional and physical consequences of lower limb amputation, the direct cost of lower extremity amputation ranges from \$20,000 to \$60,000 depending on degree (e.g. toe amputation vs. transfemoral amputation) (5). Along with the amputation surgery and the hospitalization costs, the amputee needs to achieve a certain degree of mobility. Selection of the prosthetic is done after considering various patient factors such as age, weight, reason and level of amputation, other health conditions and amputee motivation. According to prosthetic knee manufacturers, for a basic prosthesis, costs range from a few thousand dollars for passive models, to about \$20,000 for microprocessor equipped models and \$100,000 for powered models.

The prosthetic knee market provides the amputee with many choices including purely passive, hydraulic, pneumatic, friction-based and powered models. Current generation prostheses, except for purely passive models, are supplemented by microprocessors and a variety of sensor techniques such as electromyography, knee angle sensors, heel strike/toe off indication switches and foot load cells. Nevertheless, the gait quality of transfemoral amputees has not improved significantly in the last 50 years. This is due to inefficient knee joint energy flow distribution of commercial prosthetic knees along with an

absence of proper knee flexion during the swing phase. This causes the patient to hike his/her pelvis up leading to back pain over time. In this context, state-of-the-art prosthetics technology is trending toward creating energy regenerative devices, which are able to harvest and return metabolic energy during ambulation.

In this review, the influence of training/ comfort of the amputee and socket fitting factors are disregarded and only biomechanical aspects of the knee and ankle joints, along with the compliance between them, are evaluated.

Significance of transfemoral amputation as a clinical problem

Transfemoral amputation is one of the most traumatic medical treatments a patient can receive. Amputees not only lose physical function and neural feedback after amputation, but also have altered knee kinematics during the swing phase of the prosthetic limb, which causes abnormal pelvic movements in the frontal plane even with the most sophisticated microprocessor equipped prosthetic knees available on the market today (6-9).

In addition to the quality of life limitations, transfemoral amputation accelerates the additional deterioration of an amputee's state of health due to current design inefficiencies: walking with prosthesis requires 60-100% more oxygen consumption compared to ambulation with a healthy leg (10). Amputees also have reduced neuromuscular feedback and control (11) that reduces one's sense of balance and increases the probability of falls. Another issue is that amputees are at high risk for pathological problems such as osteoarthritis (12) and lower back pain (13) due to improper pelvic movement in the frontal plane. Additionally the center of pressure (CoP) at foot contact on the prosthetic side is further away from the center of mass (CoM) on the intact side. This increases the probability of falls due to abnormal gait patterns causing additional metabolic, physiological and psychological consequences. Farahmand et al. (14) have reported that an amputee's intact side hip joint experiences a larger extension hip moment and flexion knee moment than a healthy subject while the hip joint on the amputated side experiences a lower extension hip moment. This suggests that the muscle activity of an amputee during ambulation is higher than for an individual with a natural gait pattern. Specifically, the adductors in stance phase and abductors in swing phase are weakened significantly, that causes less muscle force generation during ambulation (15). Previous research stated that another reason for asymmetrical ambulation is irregularity in

stance phase kinetics. The result of abnormal and unequal loading on the intact side and the prosthetic limbs during the stance phase causes insufficient swing phase knee flexion, therefore the CoM of the prosthetic limb disproportionately rises (16,17). Furthermore, due to the stance phase kinetics. The result of abnormal and unequal loading on the intact side and the prosthetic limbs during the stance phase causes insufficient swing phase knee flexion, therefore the CoM of the prosthetic limb disproportionately rises (16,17). Furthermore, due to the inadequate swing phase knee flexion, an amputee needs to raise his/her hip, which causes asymmetrical ambulation and amplifies the metabolic power required to complete the stride. The majority of these problems are caused by asymmetric gait patterns forced by prosthesis limitations. In order to minimize the metabolic energy expenditure and reduce the need for muscular recompense of a trans-femoral amputee, the overall energy distribution during the stance and swing phases should be balanced appropriately by the prosthesis to provide close to normal ambulation and minimize the aforementioned limitations

Commercially available prostheses

Prosthetic knees on the market are classified into three categories: passive, microprocessor equipped and powered. Passive prostheses do not include control and/or sensor units to manipulate the phases of gait, therefore they are unable to sense the knee angle and/or apply ground reaction force to respond accordingly. They provide ambulation by using their purely passive and non-computerized mechanisms, which cause not only flaws during the swing phase but also incremental net metabolic energy consumption during activities of daily living (18).

Passive knees are able to accommodate walking on even surfaces at various cadences without providing the required positive energy back to the system. However, they are not capable of providing successful ambulation on uneven surfaces and during positive energy dependent activities, such as sitting down/standing up and stair ascent/descent (19). Consequently, the patient is constrained to perform these activities with a step-by-step technique where the loading is applied on the healthy leg while the prosthetic limb follows passively.

ÖssurMauchStanceNSwing (SNS), is a passive friction-based prosthetic knee designed to allow amputees to walk at various speeds using hydraulic fluid flow to control the piston as it forces fluid out of staggered holes to simulate muscle movement (20). During the stance

phase, hydraulic fluid flows through narrow orifices in the hydraulic cylinder, which increases stiffness and provides needed weight bearing support. During the swing phase hydraulic fluid flows through wide orifices and permits knee joint flexion.

By incorporating software algorithms, microprocessor equipped prosthetic knees are able to provide more efficient ambulation on uneven surfaces and during activities of daily living than passive models (18,21). Powered prosthetic knees are composed of miniaturized motors, which require an electrical power source, that mimic muscle contractions and provide the required positive energy during ambulation. However, they are heavy (a Power Knee weighs 4700 g, whereas the average weight of a commercial microprocessor equipped knees is 1250 g) and relatively more expensive (Power Knees cost \$100,000 whereas, the average cost of a commercial microprocessor equipped knee is \$20,000).

Microprocessor equipped prosthetic knees provide more natural walking than the passive designs do by improving gait smoothness, reducing overall work at the hip joint and at peak hip power generation at toe-off during controlled walking speeds. When they are compared with passive knees at self-selected walking cadences, no significant difference in energy consumption was observed (18,22-24). In another study, Schmalz et al. (25) presented that C-Leg had a minor advantage over the Mauch SNS with self-selected walking speeds. Similarly, in Johansson et al.'s findings (18), the energy consumption of Rheo Knee was 5% lower than Mauch SNS and 3% lower than the C-leg at self-selected walking speeds.

Unlike the situation with a natural leg, where energy can be stored in tendons, neither passive nor microprocessor equipped prostheses can store and release energy at chosen times which would help propel the patient's forward motion by providing the required positive energy. They can only simulate joint resistance and damping, meaning that the truly natural motion of the leg is limited.

Power Knee is the first and only active commercial prosthetic knee on the market (26). Its total weight is 4700g, which makes it significantly heavier than the passive and microprocessor equipped prosthetic knees (Rheo Knee: 1520g, C-leg: 1147 g, Mauch SNS: 1200g) due to motors and batteries. It uses the orthosis- Artificial Proprioception Module (APM) coupling, which communicates with the functional leg of the amputee and mimics its movements. The orthosis sensor

unit is worn on the intact leg collecting and transmitting real time data. The APM, located on the ankle of the Power Knee limb, receives this instantaneous data and sends it to a microprocessor. It is a rarely used prosthesis because it has not yet been given a Medicare insurance reimbursement code due to the high price and that reports on its performance are scarce in the literature. Currently only two Iraqi war veterans are using the Power Knee (26). In addition to its significantly high weight, it can only be used by unilateral transfemoral amputees as the APM needs the real time data collected by the orthosis. Among people who live with limb loss, only a fraction are bilateral transfemoral amputees (approximately 18%) (27). In addition to the significantly high market price drawback of the Power Knee, when the dramatically increasing obesity and diabetes rates are considered, it is anticipated that the number of bilateral transfemoral amputations will also increase, which will reduce the number of potential Power Knee users.

Emerging prosthesis designs

Motivation

One significant drawback of the inability of delivering positive energy when needed, found in commercial passive and microprocessor equipped prosthetic devices, is due to the absence of knee flexion during the stance phase. Moreover, consequences such as circumduction and disturbed gait pattern take place due to improper energy flow at the knee joint and the absence of positive energy delivery during the swing phase. Current generation powered design has solved these problems by delivering the necessary energy with heavy battery demanding motors. This increases the mass of the device significantly, whereas, it needs to be relatively less than the mass of the missing portion of the natural leg. Patients want a knee prosthetic device that is lightweight, quiet, and capable of delivering close to normal ambulation. The combination of these three features in prosthetic limbs has proven to be difficult to provide. Patients want the prosthesis to be similar to the normal leg, including normal knee and ankle flexion angles during activities of daily living (28). Thus, prosthetic knee developers sought new methods to design efficient mechanisms which are lightweight and at the same time energy regenerative.

A new approach utilizing spring mechanisms for improving energy efficiency during gait is found in gaining traction (29-33). Since gait is a cyclical pattern that has positive and negative work phases, using a spring can cut the power demand significantly when mimicking the musculotendinous structures by harvesting and returning the needed energy.

A significant advantage of the spring is its high efficiency and high power-to-weight ratio (34). Instead of using heavy motors, gearboxes and bulky batteries, a spring can help provide the peak power demand of the prosthesis during the stance phase of gait with less weight.

Unal et al. (35) at the University of Twente, The Netherlands, developed a completely passive transfemoral prosthetic knee prototype which is capable of harvesting and returning energy by using a set of springs, coupling knee and ankle joints. The design of this knee is based on the balanced energy distribution in the ankle and knee joints during a single stride. The ankle joint behaves as an energy generator during the pre-swing phase and stores 80% of the required energy (35). During walking, the amount of energy generated by the knee joint in the stance flexion phase, and by the ankle joint in the early swing phase, are stored in the spring couplings. This provides energy to the knee joint during early swing and swing phases, and to the ankle joint during the early stance phase. Stance and swing phase performance were simulated separately. The results indicated that the prototype was able to store 76% of the required energy in the spring sets and distribute it to the knee and ankle joints throughout the stride by compressing, locking and releasing the springs according to the applied body weight. However, this design is not capable of producing ankle push-off force, as it is neither controlled nor powered. Therefore, for achieving near normal walking during other activities, which require more energy than walking, hybrid designs, which unite the passive mechanisms with smart control algorithms, are needed.

SymBiotechs XT9 (SymBiotechs, UT, USA) is a patented (Registration Number: 3236824) commercial passive prosthesis, which uses a spring mechanism to mimic the functions of the quadriceps during high activity sports. It compresses the spring pneumatically depending on the applied force. However, it is not designed for normal daily use. Emerging designs take the advantages of using the high efficiency of a spring unit not only in storing and releasing energy during gait, but also in developing light, less expensive and energy regenerative prostheses, which are able to harvest energy from the movement of the user. Instead of releasing this harvested energy immediately, they will keep it until the energy is most needed during the swing phase.

Prostheses mimicking muscles

mIT, Vanderbilt University and Cleveland Clinic Foundation proposed transfemoral prosthetic device designs recently. Even though none of them have been commercialized yet,

the mutual characteristic of these designs is the use of a spring element to efficiently manipulate the energy distribution throughout the gait cycle and obtain close-to-normal ambulation via energy regeneration. This is accomplished by harvesting energy from the gait and returning it at critical times, to minimize the size and weight of the drive systems and power supplies that assist knee rotation.

The MIT team proposed powered knee prosthesis with two series-elastic actuators and spring elements positioned in parallel in an agonist-antagonist arrangement (33). Stance and swing phases are controlled by two actuators composed of a series of springs, transmissions and torque sources. Stance phase is manipulated by compressing the extension and flexion springs. The flexion and extension motors keep the springs locked when to store energy and unlocked to release it when needed.

Stance and swing phase stability is controlled by dividing the gait cycle into five phases. Stance phase is divided into three, and swing phase is divided into two sub-phases, based on loading and knee angle dynamics of reference to able-bodied human gait. During the heel strike phase, the extension spring is compressed as the amputee applies weight on the prosthesis. With that intention, the energy required to manipulate the stance extension phase is stored in the extension spring. During the stance extension phase, the knee angle reaches maximum extension, and returns the energy stored in the extension spring by releasing it. This energy is transferred to the flexion spring as the knee prepares to flex at the end of the stance phase. The compressed flexion spring causes the knee angle to reach the maximum knee flexion ($\sim 60^\circ$) and releases the stored energy.

During the stance phase, motors are only used to keep the springs compressed to store energy. Power consumption is minimized as the prosthetic knee design also benefits from gravity and the moment of inertia during the stance phase. Conversely, during the swing phase, required damping is obtained by activating the springs electrically. Therefore, during the stance phase the motors are engaged as the supplements to the mechanical systems. Conversely, during the swing phase, mechanical systems become the supplementary element to the electrical components.

The human tests indicated that the knee torque, knee angle and power of the amputee match corresponding measures for the non-amputee subject. Moreover, the prosthetic knee was satisfactory in providing near-normal walking at self-selected walking speeds on an even-surface by storing

positive energy throughout the stance flexion phase producing natural movement during push off (33).

Conversely, it has been tested only at self-selected walking speeds, where the power requirement is at minimum level. Additionally, it has been reported that for walking at variable speeds, the springs on the flexion and extension axes need to be replaced with softer and stiffer springs respectively in order to provide the required knee stiffness to the amputee. Likewise, for the activities other than walking at self-selected speeds, using linear springs on the axes would not be an option to any further extent, such that they need to be replaced by non-linear springs, which makes the control more complicated.

The Cleveland Clinic Foundation team proposed a micro-processor equipped prosthesis, which is capable of harvesting/ returning energy in a controlled way (31). Its hydraulic mechanism is composed of a linear actuator, two accumulators and two valves. The linear actuator converts pressure to torque and torque to pressure. During stance phase, as the patient's weight creates pressure, hydraulic flow is initiated through the high-pressure accumulator to obtain the required stiffness. When the applied weight starts to decrease, the accumulator pressure is routed back to the actuator to apply torque, which is needed to flex the knee. The high and low pressure valves open and close dependent on the gait cycle phase in order to permit high pressured flow from/to the actuator. The high-pressure accumulator provides energy storage and release, while the low pressure accumulator houses the hydraulic fluid in the system. The electrical/electronic system includes the micro-processor, knee angle and leg force sensors.

At the beginning of the stance phase, body weight acts on the leg and starts flexing the knee. With the high-pressure chamber of the actuator connected to the high-pressure accumulator, this torque pumps the fluid into the high-pressure accumulator, which houses the energy storage unit. As the pressure is applied, a spring is compressed and energy is harvested. Once the available energy has been stored, the control valve of the high-pressure accumulator closes and holds the pressurized fluid in the accumulator. Modulating the orifice size of the low-pressure valve maintains the desired pressure/knee torque. In late stance/early swing phases, it is closed and the high-pressure valve is opened to produce the torque needed in the actuator to initiate the knee flexion. Only optimal control simulation results during walking, running and sit/stand/ sit sequences, are available in the literature, showing that the proposed

device provided near normal knee movement and stance phase flexion when the accumulator stiffness was adjusted to each tested activity (31).

A new approach: union of ankle and knee joints

Goldfarb team (29,30,32) in Vanderbilt University proposed a powered knee and ankle prosthesis, which is powered pneumatically and capable of doing impedance control by using the feedback coming from its on-board sensors. The prosthesis is composed of two axes, on which knee and ankle actuators are located. The two servo valves, according to the feedback coming from the knee and ankle load cells, alter the stiffness of the actuators. A spring unit on the ankle control axis provides knee flexion during early stance, therefore it not only reduces the energy required to flex the knee during the swing phase, but also stores the available energy.

Stance and swing phase stabilities are controlled by dividing the gait cycle into four phases: stance flexion, pre-swing, swing flexion and swing extension. Within the gait phases actuators are kept inactive to maintain constant stiffness. In between the gait phases the stiffness is changed dynamically in order to provide the required stiffness in the knee and ankle axes, depending on the biomechanical demands of each particular gait phase.

Vanderbilt University's knee is the only transfemoral knee which unites the knee and ankle joints in one mechanism to produce the required positive energy. The powered-tethered prototype was attached to an able-bodied adult male subject via a bent-knee adaptor. The subject was asked to walk on a treadmill at three controlled walking speeds (2.2, 2.8 and 3.4 km/hr) (29). An external 2.2 MPa pressure source, along with a computer, were used to operate it during testing. The behavior of the prototype between and within the four gait phase modes was analyzed and compared with able-bodied human gait (29,32). The results showed that the prototype was able to manipulate the subjects' gaits satisfactorily by producing three positive power peaks during the stance phase. However, due to its design constraints, the ankle actuator is capable of providing 76 percent of the maximum torque during the stance flexion phase since in order to maintain the weight of the prototype within the desired range, the team aimed to limit the maximum weight of the battery unit to 600-700 g. With that battery capacity, 4.4-5 km of walking range could be obtained at self-selected cadences. Klute et al. (36) reported the daily average number of steps of transfemoral amputees wearing a C-leg as 2657 ± 737 . The average step

length of a trained C-leg user is reported as $0.72\text{m} \pm 0.07$ (37), hence the distance that a trained C-leg user walks per day is approximately 4 km. Therefore, the proposed design almost reaches the limits of C-leg capability in terms of the delivered ambulation distance.

The emerging designs are breakthroughs when they are compared to the current generation prostheses by storing energy in a spring during early stance and returning it in late stance, but these current designs are effective over a limited range of conditions and are usually directed at a narrow sports activity (29,33). A regenerative prosthesis could be a significant step forward with respect to improving the average activity level achieved by transfemoral amputees.

Discussion

A handicap with respect to designing new prostheses is a lack of broad-based data sets covering energy flows at the knee and ankle joints for a range of subjects, over a range of conditions. The margin of "negative" work at the knee over the "positive" work determines the required efficiency if the prosthesis is to be wholly regenerative (Figure 1) (38). The match between the input and output impedances gives some indication of the difficulty of achieving high efficiency in a simple mechanism.

Equally importantly, stiffness of the energy storage element, for not only a wide range of activities but also during each sub-phase of gait cycle, should be analyzed for ankle and knee joints. Stiffness of the healthy ankle joint during walking at variable cadences has been investigated by Hansen et al. (39) with the purpose of guiding the designers in developing ankle joints which are capable of optimizing the energy flow and providing a near-normal ambulation. This study focused on the torque vs. ankle angle during loading and unloading conditions. The area between the hysteresis curves during walking at self-selected speed was almost zero, however, for controlled speed walking, larger hysteresis areas were obtained. This confirms that as the magnitude of the positive energy demand increases, the supplementary mechanisms, which control the spring compression/ release, become more crucial for activities such as walking at controlled speeds, stair ascent/descent, sit/stand/ sit sequences and running, purely passive mechanisms require the support of high-level arrangements such as series-elastic actuators (33) and valve operated, spring loaded hydraulic accumulators (31).

The normal gait during any activity of daily living is a combination of different body segments' motions with the

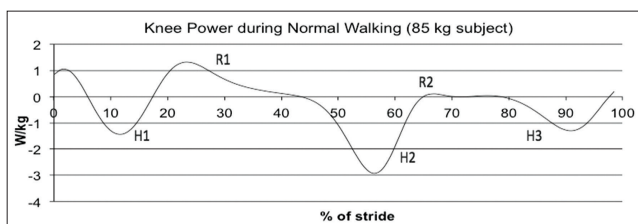


Figure 1. Knee Joint Power during Self-selected Walking Speeds- The positive power peaks, indicating energy generation by muscles (R1 and R2); and negative power peaks, indicating energy harvest by muscles (H1, H2 and H3) of an able-bodied human at self-selected walking speeds. Note that muscles act as a brake more than half of the time, which requires effective energy flow at the knee joint for a smooth and close to normal ambulation. At a glance, storing energy in the spring during H1 phase and releasing it immediately during the R1 phase, where energy is generated, might seem to be the right solution to fix the energy flow deficiency at the knee joint. However, for the H2 phase, releasing all of the stored energy during R1 phase would be disadvantageous since this may cause the toe to stub the ground right after the H2 phase because the energy at R2 is actually produced by the ankle joint and transfemoral amputees cannot generate H2 as able-bodied people because of the absence of an ankle joint.

purpose of translating the body with minimized energy cost (40). Human locomotion is a complex process, involving the interaction of many muscle groups and sensory systems. Traditionally, researchers consider six determinants of gait: (1) Pelvic rotation (lateral rotation of the pelvis), (2) Pelvic tilt (frontal plane rotation of the pelvis), (3) Knee flexion in the stance phase (knee sagittal rotation), (4) Foot mechanism (foot motion and dynamics during stance phase), (5) Knee mechanisms (knee motion and dynamics during stance phase), and (6) Lateral displacement of the pelvis (produced by relative adduction at the hip) (41). These six determinants integrate together to minimize energy consumption, maintaining a sinusoidal pathway of low amplitude for the center of gravity of the body. Based on the foot and knee mechanisms determinants, the motion of ankle, foot, and knee are closely related. For instance, during normal gait cycle, knee flexion after mid-stance is partly contributed

by rapid plantar flexion of the foot; hence, there is enough clearance for the leg to swing without stumbling during the swing phase. It has also been extensively pointed out that when walking on level ground, the knee joint muscles absorb energy while many of the hip and ankle muscles are generating energy (42-44). Therefore, even with a prosthetic knee, which is able to produce exact function of the knee, without a proper cooperation and design of the prosthetic foot/ankle joint, it is unlikely to design prosthetic devices which allow the transfemoral amputees to maintain the center of gravity at a similar sinusoidal pathway and minimize energy cost during gait cycle.

Conclusion

In spite of the fact that several prosthetic knees have been commercialized, and used for many years, none of them can mimic able-bodied ambulation, especially during activities requiring more positive energy, such as stair climbing and running. Emerging designs are trending to elaborate the efficient energy flow at the knee joint by storing and releasing energy in a controlled way in a spring unit to obtain assisted gait. Yet, they have been tested under a limited array of conditions and their energy flow performance during activities, other than walking at different paces, is still unknown.

The literature is missing a comprehensive analysis of energy flow at the knee and ankle joints during the activities of daily living. The analysis of impedance matching and the spring stiffness of the energy storage unit, which participates in harvesting and generating the right amount of energy in a controlled way, is essential across the sub-phases of the gait cycle, during a wide range of activities, in order to understand the requirements of transfemoral amputee gait and design energy regenerative devices.

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