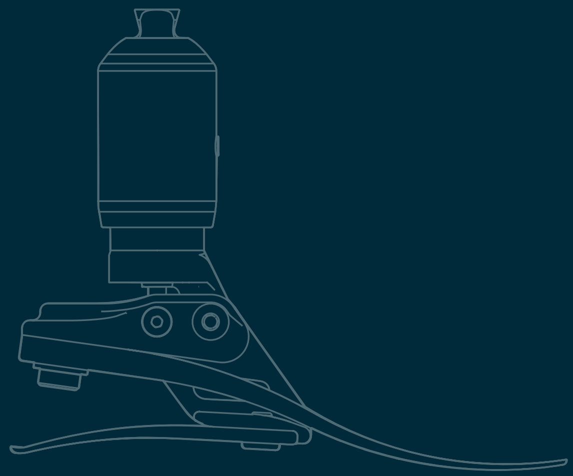


A Study of Hydraulic Ankles

Blatchford

Hydraulic Ankles

Over a decade after challenging conventional wisdom, new scientific evidence continues to be published on the medical advantages of hydraulic ankles.

In humans, each foot is composed of 26 bones – together making up 25% of all the bones in the whole body. In addition, the foot also contains 30 different joints and more than a hundred muscles, tendons and ligaments. This complex design allows us to move and balance over a variety of different surfaces, usually without even thinking about it.

The prosthetic foot has always been a much simpler design. It has long been based on the concept of storing and returning energy as efficiently as possible. This is achieved using carbon fibre spring-like elements which deform during weight acceptance, storing energy, which is then returned as the user pushes off with their toe. This helps to restore some of the propulsion that would ordinarily be provided by ankle muscles.

However, the ankle in such designs is usually fixed to ensure efficient energy transfer. This means that they rely on the flexibility of these spring-like elements to adapt to uneven ground. Previous studies have reported this lack of adaptation to be a drawback for conventional prostheses[1], as such, most prosthetic users have some difficulty walking on ground that isn't completely flat[2,3].

The introduction of hydraulic-damping ankles to address this was a controversial one, going against the teaching and understanding of prosthetic biomechanics at the time. How could this technology be of benefit to the user when it affects the efficiency of energy return?

Biomimetics of the Ankle

Biomimetics is the ability of a design to mimic the natural behaviour of the thing it is replacing. Conventional energy-storage-and-return (ESR) prosthetic feet rely on the deflection of the carbon fibre 'heel' and 'toe' springs, in order to produce the 'rollover' mechanism of the foot during walking. From an engineering perspective, this can be modelled as two springs, at the front and back of the ankle, which have an equilibrium point defined during the static prosthetic alignment. While the efficiency of the springs determines *how much* energy is returned, there is no control over *when* the energy is released during the gait cycle, meaning that the feet have limited adaptation to different environments.

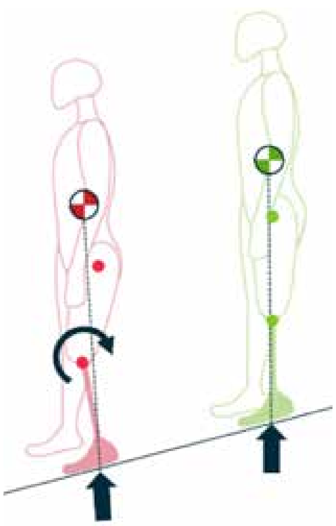
Fixed equilibrium point

Variable equilibrium point

Hydraulic ankles, provide an alternative to this conventional design, creating a more biomimetic model. This design still incorporates 'heel' and 'toe' springs, but rather than a rigid 'ankle', there is a joint. Hydraulic damping is used to influence the movement of this joint, producing a viscoelastic property closer to the behaviour of human muscle. Accordingly, this mechanism can be modelled as two spring-damper setups, which provide a variable equilibrium position. In essence, the 'ankle' can self-align and adapt.

Self-alignment

Ankle compliance with the ground is important when standing still too. On flat ground, the prosthetist will deliberately align the prosthesis to minimise the forces acting about the joints of the lower limb; the bodyweight vector should act in front of the ankle, slightly in front of the knee and through or slightly behind the hip. With an ESR foot, the ankle does not adapt and so compensatory movements are often required when standing on a slope. One strategy is to get the foot flat on the ground by flexing the knee. This moves the bodyweight vector behind the knee, requiring the amputee to resist the resulting moment, making it more difficult to balance and more tiring to stand.



Ankle self-alignment allows upright posture and even weight distribution

An alternative is to hyper-extend the knee, pulling the weight back to the heel and lean the trunk forward. This puts the bodyweight vector in front of the hip, again creating a poor alignment and a moment that must be resisted through muscular effort elsewhere.

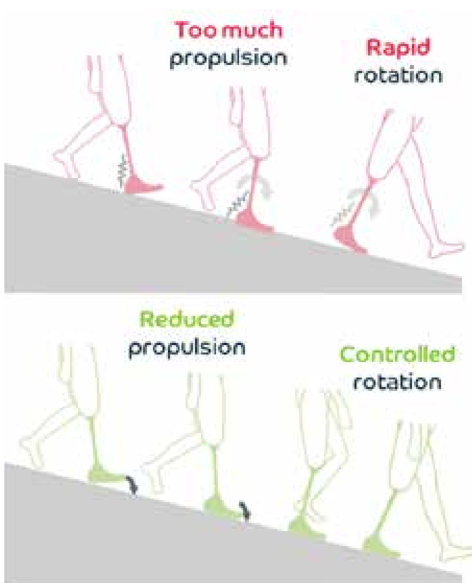
Commonly, these compensations lead to greater reliance on the sound limb to support bodyweight as well as an increase in the energy used. Amputees use more energy than able-bodied people on a day-to-day basis, when completing similar tasks. If they are also having to resist additional forces caused by malalignment, this extra effort soon mounts up.

The pressure distribution at the socket interface is also influenced by the slope of the ground[4,5], sometimes leading to discomfort or potentially causing injury to the limb. Having a foot that can adapt to different gradients maintains the correct position of the socket and reduces the likelihood of sensitive areas being subjected to high loads, thus improving comfort.

Hydraulic devices conform to the gradient of the slope, allowing the bodyweight vector to remain well-aligned, relative to the knee and hip. This permits a more natural posture and an improvement in symmetry; an outcome widely regarded as helping to reduce the likelihood of musculoskeletal health problems, such as osteoarthritis and lower back pain, which are prevalent in the lower limb amputee population[6,7].

Studies reported up to a 24% increase on the load supported by the prosthetic limb and up to a 20% reduction in that supported by the sound limb[8] when using hydraulic ankles. The result of this was better balance, as evidenced by an average 25% reduction in centre-of-pressure movement, reducing the likelihood of a fall occurring – something else that is a common problem for amputees[9].

Walking on Slopes



It is not just during standing when ankle adaptation is beneficial. When walking down a slope, it is desirable to get the foot flat on the ground efficiently, at the correct time, to provide a stable base of support. Using a conventional ESR foot, the heel is designed to propel the wearer forward, which, in this scenario, forces the lower leg to rotate forwards too quickly because the heel is designed to push the wearer onto the toe. This can lead to excessive knee flexion or increased work from the hip as the wearer tries to compensate and control their movement. With a hydraulic ankle, when the heel is loaded, the 'ankle' adapts to the surface, so the foot can become flat on the slope with the leg still in a natural position. This provides greater control of momentum because the heel spring returns less energy, reducing the need for gait compensations.

Similarly, when walking uphill with the ESR foot, the wearer must move their body up and over the foot with the toe spring acting against them. This is hard work and can lead to hyperextension of the knee. The hydraulic ankle allows a range of dorsiflexion so the leg can rotate over the foot more easily and the spring acts in the direction of progression. These advantages also translate to walking on ground that slopes from side-to-side (also known as a 'camber').

One study found the ankle moments of hydraulic ankles more closely replicated those of the user's sound ankle and those of able-bodied control subjects, compared to ESR feet, when walking on cambered surfaces[10]. This highlights the biomimetic design principle behind hydraulic ankles.

Energy Expenditure

Since the wearer is not having to fight against the foot springs, walking on slopes with hydraulic ankles is more energy efficient and less tiring. One study looked at how much energy amputees use when walking on slopes by analysing the oxygen and carbon dioxide in their breath[11]. Subjects were asked to walk on different gradients of slopes using rigidly-attached ESR feet and Blatchford's Echelon hydraulic ankle. With hydraulic ankles, they used an average of 20% less energy across the different slopes.

In the past, a preconceived misunderstanding about hydraulic ankles was that, because they absorb energy, they must be more tiring for the wearer when walking on flat ground. However, the amount of energy returned is not the only consideration. It also matters when the energy is returned during the walking cycle and how the foot is oriented at the time.

For a biological ankle, during walking, the muscles use concentric and eccentric contraction to control the rate of weight acceptance, prevent foot-slap and manage how fast the leg, and rest of the body, progresses forward. Hydraulic ankles aim to replicate this 'visco-elastic behaviour' through the adjustment of valves, allowing for customisation of ankle rotation and the energy stored in the heel and toe springs.

The same study[11] also looked at how much energy amputees use when walking on flat ground at different speeds using the same two prosthetic foot designs. With hydraulic ankles, they used an average of 12% less energy across the different walking speeds. This meant for the same amount of energy, the subjects were able to walk up to 7% faster with their hydraulic ankles.

Better Mobility

When patients select their own walking pace, speed increases by up to 8%[12–14] and progression through the gait cycle was found to be smoother[14,15].

The fact that amputees will naturally select a faster walking speed when using hydraulic ankles is indicative of better energy management from the prosthesis. Faster walking naturally increases the forces on the body but when this increased walking speed is taken into consideration, hydraulic ankles have been shown to significantly reduce the amount of work done by the sound limb by an average of 17%, which improved the symmetry of loading between limbs. Reducing the demand on the sound limb during walking may reduce the chance of osteoarthritis development; a condition often observed in amputees[6].

Reducing the loading on the sound limb has other benefits too. The most common causes of lower limb amputation are dysvascular conditions, such as diabetes, with studies reporting these conditions as the cause of up to 82% of lower limb amputations in the United States[16]. These often stem from the development of pressure ulcers under the foot, which go unnoticed and untreated[17]. For people with dysvascular conditions who already have an amputation, one in ten will require an amputation on the contralateral limb within 12 months[18] so protecting the sound foot is of upmost importance.

A study looking at pressure under the contralateral foot of amputees reported that there was an average 24% reduction in peak pressure when the subjects wore hydraulic ankles, compared to rigid or elastic prostheses[19]. This has a significant health benefit to the contralateral limb. It is also likely that the reduction in gait compensations, such as hip-hiking, contributed to this observation.

It is not just the forces on the sound limb that needs to be considered. Dysvascular amputees will have vulnerable residual limbs too. In these cases, soft tissue is more susceptible to damage[20], does not heal as well as healthy tissue[21] and may be affected by peripheral neuropathy allowing tissue breakdown and damage to go unnoticed. Just as diabetic foot ulcers can develop and lead to amputation in the first place[17], pressure ulcers on the residual limb are a major concern for prosthesis wearers[22,23]. Of those patients that develop pressure ulcers in hospitals, 34.5% are medical device related[23]. When a patient has vascular comorbidities, 24% of trans-tibial and 14% of trans-femoral amputees will require revision surgery or reamputation at a higher level within one year of the first procedure[18]. Obviously, protecting the residual limb is therefore of paramount importance.

The differences in pressure at the residual limb interface were investigated when walking with an ESR foot and a hydraulic ankle[24]. When walking over various terrains, such as paved floor, grass, stairs and slopes, peak pressures on the residual limb were reduced by up 81% with the hydraulic device. The rates of loading were also reduced up to 87%. These differences are likely to be protective against pressure ulcer development.

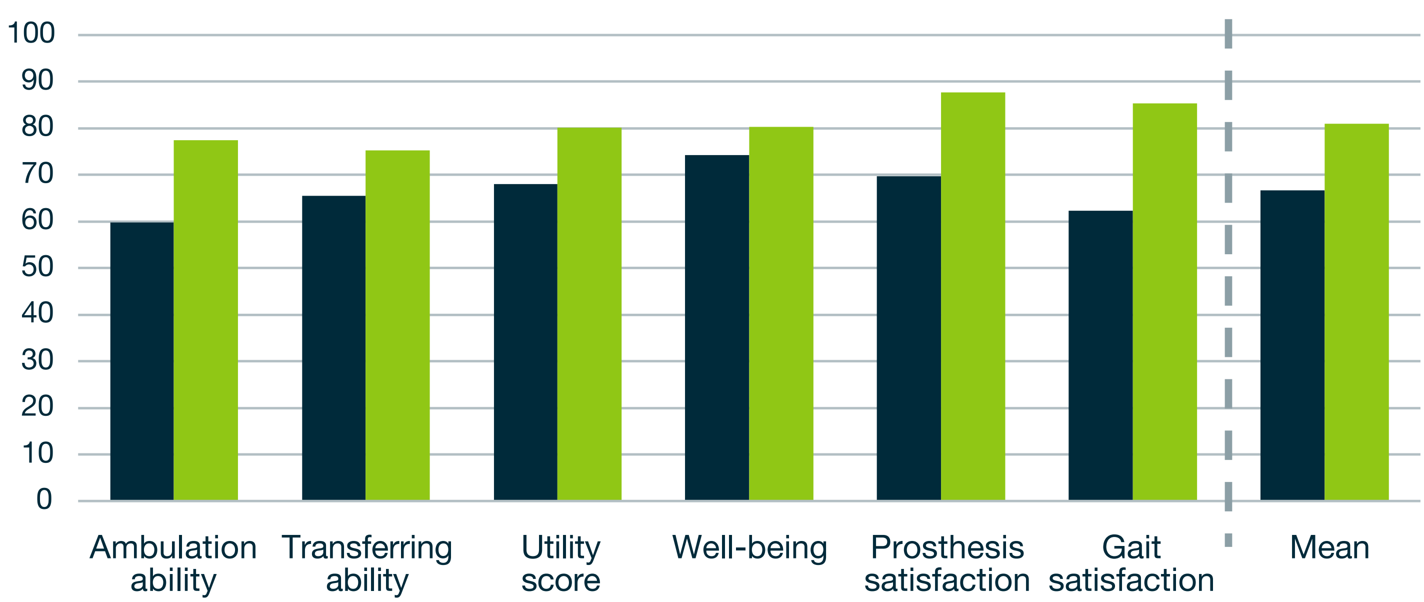
Reducing Fall Risk

During stance phase, loading and energy management is important; during swing phase, the goal is to position the foot correctly, without catching the toe. Falling is a major issue for amputees[9], caused by loss of balance and tripping in equal amounts[25]. The loss of muscle function and proprioception in the lower limb mean that toe

Dorsiflexion in swing phase gives greater clearance

Combined PEQ scores for Echelon/Avalon^{K2} v standard feet

Standard foot   Hydraulic foot



clearance (the distance between the toe and the ground during swing phase) is compromised after an amputation, increasing the likelihood that the toe will catch, causing the user to trip. The motion of hydraulic ankles places the foot in a dorsiflexed position at the end of stance phase and it remains that way during swing. As a result, there is an average 18% increase in the minimum toe clearance with hydraulic ankles, compared to rigidly-attached feet[12]. This dorsiflexed position also has the added benefit of providing shock absorption and cushioning as the ankle is able to move through its full range during stance phase.

User Satisfaction

Hydraulic ankles don't just perform well under test lab conditions. Using the Seattle Prosthesis Evaluation Questionnaire[26] (PEQ) as a measure, two separate studies assessed the difference between patient evaluation scores; one comparing Echelon to ESR feet for K3 users[27] and the other comparing Avalon^{K2} to Multiflex feet for K2 users[28]. The patients completed the evaluation about their current prosthesis, assessing how well they were able to complete certain mobility tasks, as well as how they perceived their prosthesis and aspects of their life affected by their amputation. They were then fitted with the hydraulic device and used it in their daily lives before completing the evaluation again.

After four weeks, scores had improved across the board, with the Avalon^{K2} averaging a 23% increase across all categories[28] and the Echelon averaging a 21% improvement[27]. The biggest differences were seen in the ambulation score, prosthetic satisfaction and gait satisfaction categories. Within ambulation score, Avalon^{K2} users showed a 29% increase and Echelon users a 30% increase, indicating an improvement in their functional mobility. Both prosthetic and gait satisfaction scores, that is how each user perceives their prosthesis or the way they walk, increased drastically, especially gait satisfaction where Avalon^{K2} users reported a massive 42% improvement!

Lower-mobility Prosthesis Users

Approximately 75% of lower limb amputees are over 60 years of age[29,30]. Age can place further restrictions on mobility so there is a need for advanced technology that is specifically focused towards the biomechanical needs of this population.

Blatchford's Avalon^{K2} combines a purpose-designed, solid keel foot with hydraulic ankle technology. In addition to the self-perceived improvements already mentioned[28], low mobility users saw an increase in walking speed of approximately 6.5% when using the foot[31]. Inter-limb loading symmetry was also improved, concurred by later research that found asymmetry of the time spent on each limb during walking was decreased by a mean of 34% for Avalon^{K2} users, compared to their previous rigid or elastic ankle devices[32].

Microprocessor-control

Microprocessor-control has been a well-established part of prosthetic knee control since the early 1990s, but similar technology has only been translated to the prosthetic ankle-foot in the last decade or so. Blatchford's Elan microprocessor foot is based on hydraulic ankle technology and adapts the amount of resistance that the joint provides throughout the gait cycle. By changing the resistance to dorsiflexion and plantarflexion, independently, the biomechanical behaviour of the prosthetic ankle joint can provide a closer representation of biological ankle function.

Microprocessor braking effect downhill helps to control momentum

When compared to elastic feet on flat ground, Elan retains all the benefits provided by previous hydraulic technology. A direct comparison between Elan and an ESR foot with an elastic ankle was made and repeated over a year later[33]. Elan presented consistently faster self-selected walking speeds and the changes to the residual knee moment meant that greater bodyweight support was provided by the prosthetic side.

When walking downhill, the plantarflexion resistance is automatically decreased compared to level walking. This allows the ankle to rotate more easily, improving ground compliance, storing less energy in the heel spring and reducing the speed of rollover. At the same time, resistance to dorsiflexion is increased, controlling the rate at which the leg rotates over the foot. The combination results in an overall braking effect to prosthetic movement, increasing stability and giving the user more control when going down slopes.

Many studies have compared the effectiveness of Elan to both rigidly-attached feet and non-microprocessor hydraulic ankles for downhill walking. When walking down slopes, Elan was shown to reduce knee flexion by up to 15% at loading response[34], while easier plantarflexion (due to the lower hydraulic resistance) allowed the foot to comply with the ground up to 8% faster. This ankle movement provides shock absorption, reducing compensatory movement at the residual knee. In addition, the braking effect from the increased resistance to dorsiflexion reduces the speed of lower leg rotation by up to 9%. Not only does this help control the build-up of momentum, it improves knee stability[35], reduces the impact on proximal joints[36] and helps the prosthetic side to provide greater support of bodyweight[37]. In one study, this support increased by an average of 26%, resulting in less reliance on the sound limb of up to 8%[37].

When walking uphill, plantarflexion resistance is increased, therefore storing and returning as much energy as possible within the heel spring, while dorsiflexion resistance is decreased, allowing easier progression of the leg over the foot. This helps to propel against gravity and facilitate forwards rotation of the limb. Studies have shown that these changes in resistance, whilst walking uphill, reduce the demand for support placed on the sound limb, this time by an average of 7%[37], and improve the biomimicry of the ankle moment[35].

Overview

Current studies highlight the potential patient benefits of using hydraulic ankles. These benefits occur in numerous areas that are known to be problematic for amputees.

Loading Symmetry

More even weight bearing between healthy and prosthetic limbs

Lower risk of developing osteoarthritis or lower back pain

Energy Expenditure

Less tiring to use

Less demand on the healthy limb

Pressure

Less pressure on residual limb

Less pressure under the healthy foot

Protects against skin breakdown

Falls Risk

Toe clearance is increased when swinging through – less chance of tripping

Fewer trips means fewer falls

Better balance when standing on uneven ground or slopes

Gait Quality

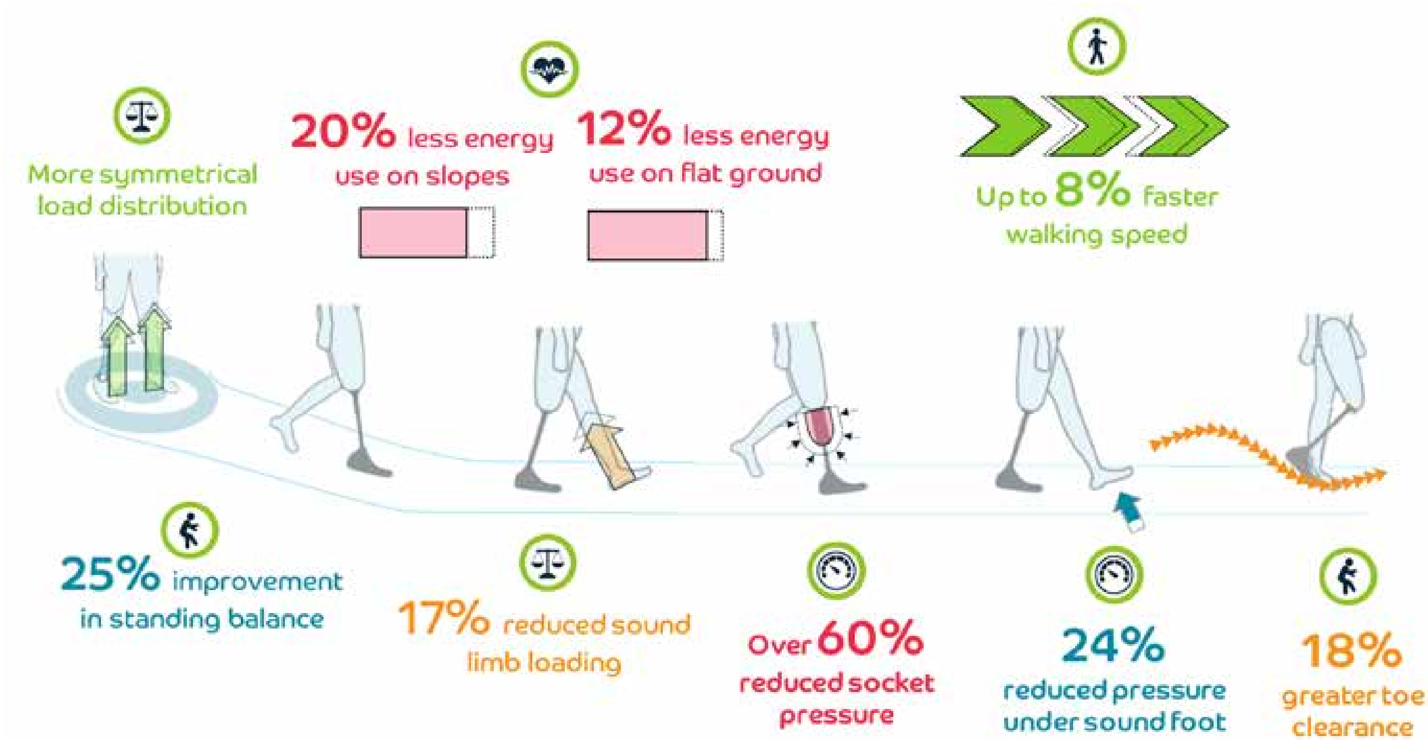
Faster walking speeds

Improved posture

More natural walking over sloped or uneven ground

User Satisfaction

Higher patient satisfaction scores for both low and high mobility amputees



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