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Stride by Stride: Assessing the Impact, Advantages, and Disadvantages of Running-Specific Prostheses

Emily Castilaw

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Ouachita Baptist University

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Senior Honors Thesis

I. Introduction

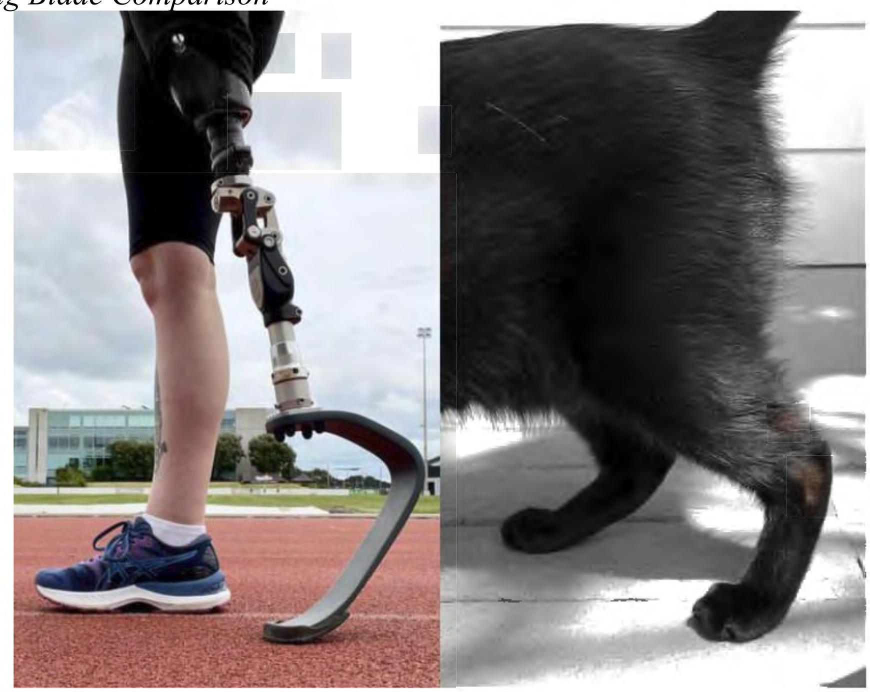
In the past 50 years, the number of amputee athletes competing in track and field has increased exponentially. From the collegiate level to international competition, amputee athletes are making their mark in history by competing at higher levels in more numbers than ever before. These athletes are competing in world events such as the Paralympics and have accomplished incredible times, which are attributed to newer prosthetic limb designs, like running-specific prostheses (RSP), also known as running blades. These devices replace the user's foot and ankle and are identified by their unique curved design. A few amputee athletes have even competed against able-bodied athletes on the NCAA Division 1 level, Olympic level, or have eyes set on future Olympic games and other professional competitions. However, many people question if these modern running prostheses provide an unfair advantage to these athletes, especially in short, explosive events such as long jump and sprinting. This belief is known as techno-doping or using technology to boost performance. In 2007, the International Association of Athletics Federations (IAAF) ruled that running blades provided an unfair advantage and banned athletes using these devises from competing against able-bodied runners; however, this decision was overruled in 2019. Should athletes that use prostheses be allowed to compete with able-bodied athletes? What rules are set to ensure fair competition? These are valid questions, but research has begun to develop answers for them. While there are both disadvantages and advantages of using running specific prosthetic devices, current research supports no substantial overall advantage over biological limbs in track and field performances. Moreover, more research must be completed to better understand this issue if amputees and able-bodied athletes compete in the future.

II. Historical Context of Prostheses in Athletics

According to the International Paralympic Committee (IPC), a prosthesis is defined as "An artificial device that replaces a missing body part, which may be lost through trauma, disease, or congenital conditions." The initial push for functional and high impact lower limb prostheses in the United States began after World War II. Young veterans returned home and wanted to remain active and involved in their life despite their new amputations. At that time, prostheses were carved out of wood and attached with leather, which did not provide much functional movement outside of standing or slow, difficult walking. Soon prostheses changed from wood and leather to metals and carbon fiber along with more natural appearances. Advances in the materials used, structure, and availability of materials have changed prosthetic design to allow for more comfortable wear and mobility. The push for amputee running began around 1980, when runners like Dick Traum, the first amputee to finish a marathon in 1979, and Terry Fox, who started the Marathon of Hope where he ran 143 marathons, or 3,339 miles, across Canada for Cancer research funding in 1980 (12), pioneered the way for amputee awareness and research for prosthetic renovation. Athletes like this demonstrated that amputees could run but did not have adequate prosthetic devices. The first prostheses created for running specifically was the "flex-foot" designed and created in 1984 by amputee Van Phillips (1). This prosthetic foot was designed for high impact activity levels. This model was significant in the development of athletic prostheses because it was the first prosthesis foot created to sustain high speeds with a model outside human anatomy. Its design was based on a cat's hind legs and built for explosive speed with optimum energy release, like a cheetah. This was the model most famously used by Oscar Pistorius who was the first amputee to qualify in track for the 2012

Olympics and competed against able-bodied athletes in the men's 400m where he advanced to the semifinals and other world athletic races.

Figure 1
Running Blade Comparison



Note: A running blade alongside the hind legs of a cat, the inspiration for the curved design (8)

In the past few decades, amputees have had the option to become professional runners and compete at elite levels due to new prosthetic designs. The first official Paralympic competition that included amputees using lower limb prostheses was in 1976 (2). In these games, the men's 100m had only two participants, J. Little and Walter Fink, where the latter won with a winning time of 42.8s. More recently, the 2021 Paralympic games were won with a time of 10.76s (3). This is almost a 74% difference in these performance times in the span of 44 years. To demonstrate how significant this is, the first ever Olympic games men's 100m in 1896 was won with 11.8s while the 2020 games was 9.8s. This would be an 18.5 % difference in the span of 124 years. Below is a graph (Figure 2a) that displays the extreme contrast between the Olympic and Paralympic winning times for the men's 100m run starting in 1976 taken from the Olympic and Paralympic archives.

Figure 2a.

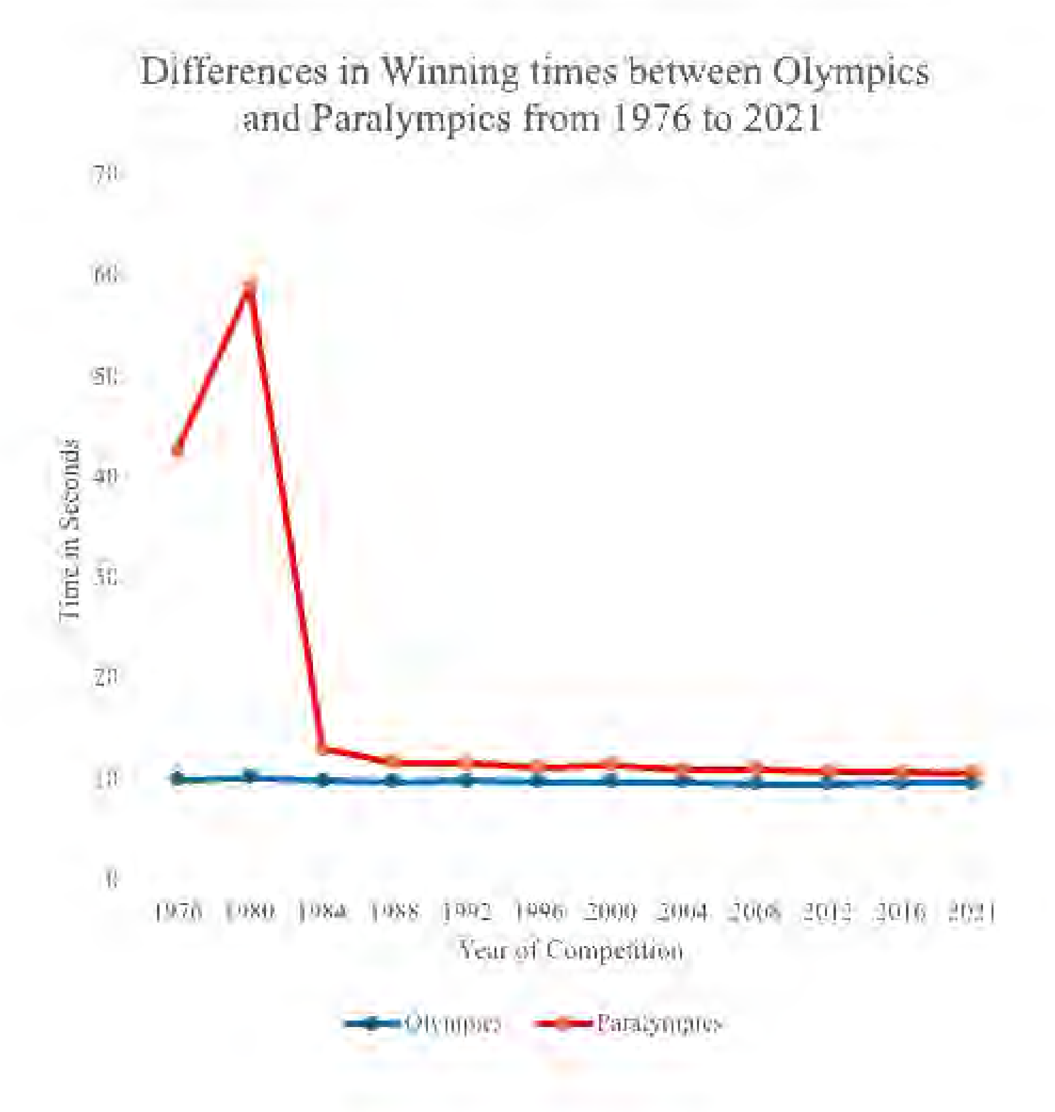


Figure 2b.

Men's 100m Winning Times in Seconds		
Year	**Olympics**	**Paralympics**
1976	10.06	42.8*
1980	10.25	59.03**
1984	9.99	13.12
1988	9.92	11.76
1992	9.96	11.63
1996	9.84	11.36
2000	9.87	11.53
2004	9.85	11.08
2008	9.69	11.17
2012	9.63	10.9
2016	9.81	10.81
2021	9.8	10.76

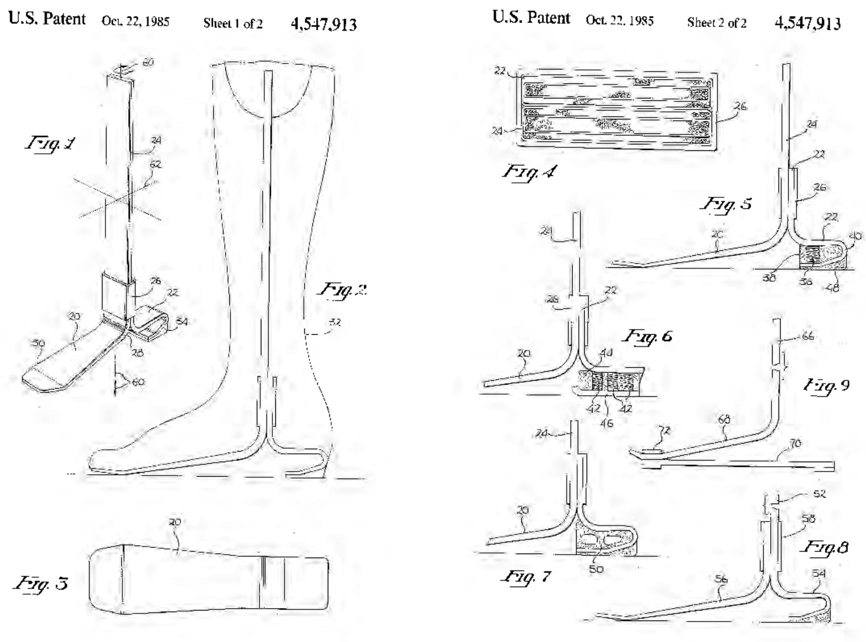
Figure 2a (top): Graph of Winning times for the Men's 100m race in the Olympic and Paralympic games from 1976.

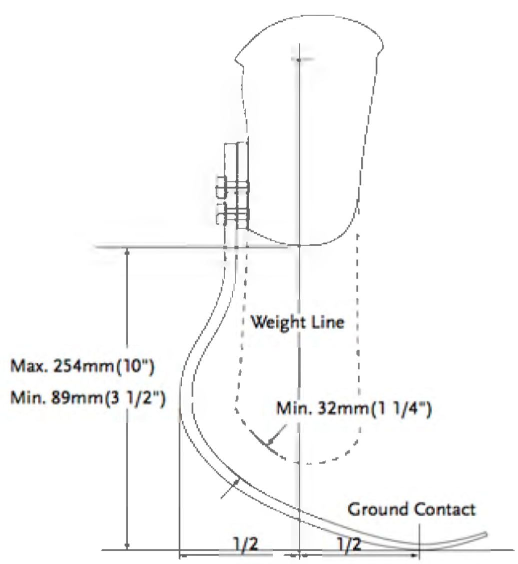
*Figure 2b (bottom): Chart of Winning times for the Men's 100m race in the Olympic and Paralympic games from 1976 the first Games that included amputees) until 2021. (Olympic Archives) (*only two participants, ** only one participant in this race)*

The extreme closing between time gaps shown are contributed to a dramatic increase of participants and improved running blade models. Other companies have followed the curved blade model which is seen in most current competitions. Since the Flex-Foot design was released, data shows that the race times of amputee athletes have improved exponentially. Today, almost 90% of amputee runners use some variation of the Flex-foot (17).

Figure 3

Original Flex-Foot and Cheetah Model





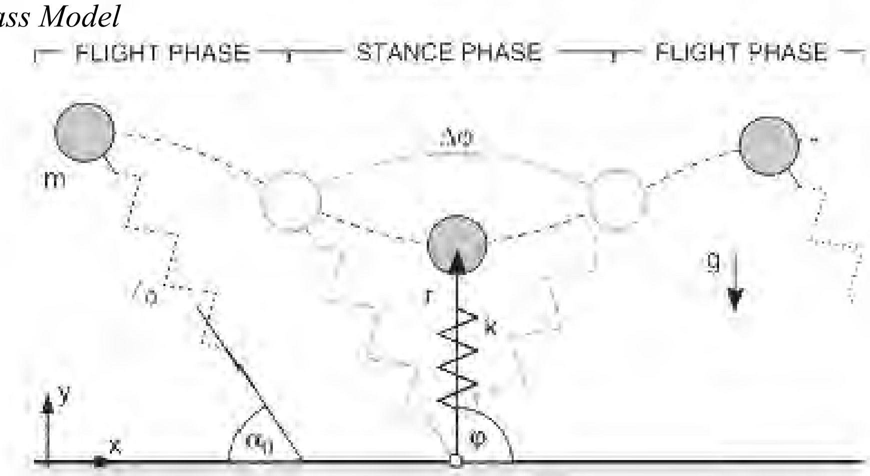
Note: Original Flex Foot U.S. Patent (top) and most recent design- Ossur Flex-Foot Cheetah from website (bottom)

III. How Running Prostheses are Created and Work.

Today, prosthetic legs are made of lightweight material, usually carbon fiber and resin. The blades are created from 30-90 carbon-fiber sheets layered one on top of another. Then the sheets are put into an autoclave that melts and fuses the resin and sheets into a solid, contoured carbon-fiber plate. Once the compound cools and is shaped, a laser or high-powered water jet carves the sheet into several running blades. Each blade can cost between $15,000 and $18,000 (13). The socket, or the part that encases the residual limb, is made from carbon fiber and various plastics. Prosthetic limbs are attached to the body through various systems: pin and lock, vacuum, or suction. Amputees wear a silicone liner, which ranges from 9mm (about 0.35 in) to 3mm (about 0.12 in) in thickness, against their skin with prostheses over the liner.

Running blades act as a 'spring' similar to a biological leg. Humans' running motion can be seen in the spring mass model by how energy is stored and released to propel runner forwards. Prostheses work the same, in that energy is stored in the curvature of the blade during the stance phase and released by the end in transition to the flight phase.

Figure 4
Spring Mass Model



Note: Spring mass model demonstrating movement of energy while running

Prosthetic alignment influences running by adjusting the positions of the lower extremity and prosthetic joints relative to ground reaction forces. The Ground Reaction Force (GRF) is the force exerted upwards by the surface that a body sits on and is equal and opposite to that exerted downwards by that body (10). In natural walking, ground forces start at the heel, directing knee and ankle movements. Between stance phase to flight phase the forces shift, requiring ankle control by plantar flexors and gradual ankle movements. Prosthetic feet alter this pattern, with heel properties affecting foot placement, ankle rigidity controlling force transmission, and knee length determining heel lift timing. Additionally, the trochanter-knee-ankle line influences the balance between knee stability and voluntary knee control during stance. When running, the able-bodied athlete's musculature, including quadriceps, knee, calf, and ankle absorbs much of the energy generated every time their foot connects with the ground. An able-bodied athlete's foot and leg has been shown to return 241% of its energy when running (16). In contrast, an RSP's curve compresses impact, storing energy and absorbing high levels of stress that would otherwise be absorbed by the amputee athlete's knee, hip, and lower back. A running blade is an estimated one-third as powerful as a biological ankle, returning approximately 90% of its energy, compared to the ankle returning 251%, during running (16). The unique shape of the blade allows the prosthetic to flex and bend to impersonate foot ligaments and musculature. Because of the C- or J-shaped segment, the kinetic energy from the user's steps distributes and provides for a vertical forward movement when the toe leaves the ground and propels the runner forward, simulating normal human gait. Most running prosthetic devices lack a heel component because they are created solely for forwards motion. Each blade can be modified for each athlete's individual running needs in terms of stiffness and length.

IV. Current Rules and Regulations

There are governing bodies that created rules for running prostheses. The International Paralympic Committee (IPC) Athletics Classification Rules and Regulations are in place for competition. Athletes are assigned a classification to compete in. For lower limb amputees who compete with a prosthesis, the categories are: T61 (double above the knee), T62 (double below knee), T63 (single leg above knee), and T64 (single below the knee) (5). Rules are in place to ensure fairness between athletes. The following are rules related to amputee athletes and prostheses for competition and come directly from World Para Athletics Rules and Regulations March 2024 (5):

Rules for classification (5):

Technical Assessment the Technical Assessment refers to the sport specific assessment conducted prior to the Athlete taking part in their first event in the Competition (First Appearance). The aim is to replicate the activity that the Athlete will do in the Event(s) that the Athlete will compete in. Importantly, the Athlete is required to execute the activity with the best effort. During the Technical Assessment, the Athlete must wear the same attire and use the same equipment (e.g., wheelchair, throwing frame, Prosthesis, Orthosis, correct implement weights) that the Athlete uses in Competition.

Ambulant/Standing Athletes Track /Jump – Classes - T35, T36, T37, T38 - T40, T41, T42, T43, T44, T45, T46, T47 - ***T61, T62, T63, T64***

General comments classes T61 – 64 These classes are for Athletes who: - are affected by lower limb deficiency or leg length difference; and - who compete with a lower limb prosthesis and who compete in running/jumping Events to be eligible, they must meeting the following MIC: Lower limb deficiency (Section 2.1.4.1); or Leg length difference (Section 2.1.7). Athletes who do not use a lower limb Prosthesis/Prostheses for competition are not eligible to compete in these Classes.

4.1.6.1 Class T61 Athletes with bilateral through knee or above knee limb deficiency competing with Prostheses. An Athlete with a combination of a unilateral above knee limb deficiency and unilateral below knee limb deficiency will also compete in this Class. Athletes in this Class must meet the following MIC for lower limb deficiency (Section 2.1.4.1); 4.1.6.2 Class T62 Athletes with bilateral below knee limb deficiency competing with Prostheses. Athletes in this Class must meet MIC for bilateral lower limb deficiency. Athletes in this Class must meet the following MIC for lower limb deficiency (Section 2.1.4.1); 4.1.6.3 Class T63 Athletes with single through knee or above knee limb deficiency competing with a Prosthesis. Athletes in this Class must meet the following MIC for lower limb deficiency (Section 2.1.4.1); 4.1.6.4 Class T64 Athletes with unilateral below knee limb deficiency competing with a Prosthesis. Athletes in this Class must meet the following MIC: Lower limb deficiency (Section 2.1.4.1); or Leg length difference (Section 2.1.7).

Rules for Measurements (5):

3.3 Determining Maximum Allowable Standing Height (MASH) for Athletes with bilateral lower limb deficiency competing with Prostheses For ambulatory Athletes running, jumping and throwing with Prostheses (i.e. bilateral above knee amputations, bilateral below knee amputations, or combined above knee and below knee amputations, bilateral lower limb dysmelia), the following formulas apply for measuring the maximum allowable standing height: For Athletes with below knee deficiencies: Males Max. height = -5.272 + (0.998 x sitting height) + (0.855 x thigh) + (0.882 x upper arm) + (0.820 x forearm) + 1.91 Females Max. height = = -0.126 + (1.022 x sitting height) + (0.698 x thigh) + (0.899 x upper arm) + (0.779 x forearm) + 1.73 For Athletes with above knee deficiencies: Males Max. height = -5.857 + (1.116 x sitting height) + (1.435 x upper arm) + (1.189 x forearm) + 2.62 Females Max. height = -4.102 + (0.509 x arm span) + 0.966 x sitting height) + 2.14

In cases of Athletes with combined above and below knee amputation (or comparable dysmelia), the formula for below knee deficiency (see above) will be taken with the measurement of the thigh on the non-affected side. All measures are taken in conformity with the ISAK standardized measures (International Society for the Advancement of Kin anthropometry). All measures are taken in centimeters (cm) rounded at 1 digit behind the comma.

3.4 Measurement of Athletes wearing bilateral Prostheses at a competition to determine whether Athletes wearing Prostheses remain within the MASH, have the Athlete wear the Prostheses and measure their standing height as follows: Athlete stands with back against a rigid pole with feet shoulder width apart, in the most upright position possible. Methods for achieving the most upright position possible are presented in Figure 4 and described below: The Athlete must be positioned so that they have contact with the pole at the following points: Head (if possible) Shoulder girdle Buttocks To achieve contact at all three points, the most posterior aspect of the blade of the Prostheses may need to be positioned behind the pole. Joint position must be as close as possible to: Neck in neutral (not extension or flexion). In some Athletes, this may mean that the head is not in contact with the wall; Pelvis in neutral (no anterior or posterior pelvic tilt); Hips in neutral (not in flexion); Knee extension It may be difficult for Athletes to maintain their balance while in this position and consequently the Athlete must be provided with the support necessary to maintain balance using their arms Figure 7: Athlete in the most upright position possible (e.g., tall chair or an assistant). The support must be high enough, so the Athlete does not have to stoop to reach it (see figure 4). The height measurement obtained must be less than or equal to the MASH. Note that the Athlete in figure 4 is positioned against a rigid pole (rather than a wall) which allows the most posterior part of the prosthesis to be positioned behind the pole if required. Figure 7

7.2 Monitoring of the use of technology and equipment (5):

7.2.1 World Para Athletics will monitor the use of technology and equipment used, or, intended to be used, at World Para Athletics Recognized Competitions to ensure that it conforms to the principles outlined in the IPC Policy on Sport Equipment. The following examples shall be considered contrary to that policy; technology and/or equipment that, in the opinion of the World Para Athletics:

7.2.1.1 provides an unrealistic enhancement of height of release in throwing events;

7.2.1.2 provides an unrealistic enhancement of stride length;

7.2.1.3 is not commercially available to all athletes, unless the athlete can establish that the:

7.2.1.3.1 technology and/or equipment is in final product form;

7.2.1.3.2 manufacturer has announced the market launch date of the technology and/or equipment and this date is within 9 months of the date of the athlete's request to use it; and

7.2.1.3.3 manufacturer has published information on the technology and/or equipment; and/or

7.2.1.4 contains materials or devices that store, generate or deliver energy designed to provide an athlete with an overall competitive advantage over an athlete not using such technology and/or equipment (unless, in relation to technology and equipment not yet commercially available or commercially available from February 2020, the athlete can establish on the balance of probabilities that the use of such technology and/or equipment would not provide *him with an overall competitive advantage over an athlete not using such technology and/or equipment).*

7.2.2 World Para Athletics has adopted provisions to enable the use of certain technology and equipment designed to provide assistance to Para athletes. Such provisions are outlined in the Competition Rules.

7.3 Prohibited technology (5):

7.3.1 Use of the following technology is prohibited at World Para Athletics Recognized Competitions:

7.3.1.1 equipment that breaches the fundamental principles outlined in the IPC Policy on Sport Equipment;

7.3.1.2 equipment that results in athletic performance being generated by machines, engines, electronics, motors, robotic mechanisms, or the like; and

7.3.1.3 osteo-integrated prosthesis.

7.3.2 At any IPC Games, IPC Competition or World Para Athletics Sanctioned Competition the World Para Athletics Technical Delegate shall be entitled to prohibit the use of any equipment prohibited by these Regulations. In every case of a suspected breach the World Para Athletics Technical Delegate must report the matter to World Para Athletics. Upon receiving such a report World Para Athletics must refer the matter to the IPC Medical and Scientific Director. Any further investigation and/or action will be determined by the IPC on a case-by-case basis.

7.3.3 World Para Athletics shall be entitled to prohibit the use of equipment either permanently or on a temporary basis (to allow for further investigation) where it considers, acting reasonably, that any of the fundamental principles of equipment design and availability are breached.

Overall, the rules for prostheses are straightforward and level the competition for all athletes competing. However, there have been complaints about the Maximum allowed standing height regulation. Maximum allowed standing height (MASH) is the formula that uses residual body parts to estimate the height of athletes to determine how long their prosthetic limb should be. This method is in place to ensure that athletes do not have disproportionate leg lengths or an unfair advantage due to leg length (19). Discrepancies are common among the MASH method because some athletes have abnormalities in their residual or remaining limbs that result in shorter measurement for their allowed height. Congenital conditions that prematurely shorten measured lengths are not considered in this standard. For example, if an athlete is born with a condition that results in shorter than average femur length, officials would still use the residual femur measurement when calculating the athlete's MASH, so they would be shorter when compared to the average leg length for an individual with regular femur length. Many athletes have spoken out via social media and other platforms to protest these regulations. In the case of Hunter Woodall, he was born with fibular hemimelia, where his legs never fully developed as a baby and resulted in shorter than average femurs. The MASH method would still measure this length and factor this into his calculated prosthetic leg length. Moreover, the International Paralympic committee sponsored a study that compared the MASH formula to other height formulas to see which is most accurate. The study concluded that MASH was not the most accurate and that different formulas should be used for different amputations and a different formula should be used for a unilateral amputee versus a bilateral amputee (19).

V. Advantages of Running-Specific Prostheses

Running-specific prostheses enhance performance factors including greater turnover rates, finishing times, and ability to utilize different curvatures and placements of the blade to boost performance compared to able-bodied athletes. Turnover rate, or the time it takes for the foot to leave the ground and touch again, is an important part of running because the number of steps taken throughout a race is related to overall performance. Especially in sprinting, step count data suggested that at an elite level, a higher step count is attributed to superior performances in races. Since running blades are lighter than a biological leg, athletes can move and position it much faster while running. Some elite amputee sprinters appear to have learned or trained to compensate for lighter limbs by swinging both legs rapidly. (7) One study found that found that amputees with RSP "took 14% shorter and more frequent steps, affirming both athlete physiology and prosthetic configuration affect running biomechanics (7)". As a result, during the stance phase of running, amputees can reposition their legs and prostheses much faster than an able-bodied runner can. This is not a direct result of the prostheses but rather from learning and training (4).

Efficient design optimized for running biomechanics give these athletes an advantage over regular prosthesis users. Running blades store and release energy more efficiently compared to regular prosthetic legs. As the blade is compressed in the loading stage it stores the energy put into it. In the take off stage, the energy is released as the curve decompresses. In a study by Beck et al., 2022, they found that the finishing times were faster than the able-bodied athletes in the last 100m of a 400m run (18). This is due to efficient energy return coupled with faster turnover rates. Running prostheses also allow for better biomechanics in some cases. During long jump events, athletes with below knee amputations have a more efficient take-off step than non-athletes by utilizing different motor control strategies (20). They do this by relying on elastic energy storage and return which results in losing less horizontal velocity. This ability to store and release excessive amounts of energy with less work from the hip and knee joint exceeds the body's natural means.

Lastly, there are several types of running blades created for different events (sprinting, long jump, etc.). These blades are categorized on design and attachment to the socket, or centrally mounted and posteriorly mounted prostheses**.** Running specific prostheses provides an advantage over regular prostheses because they are designed to help amputees run faster and they do so very efficiently. This is due to the design and ability to utilize energy. Regular prosthesis with ankle/foot cannot store the energy and release it in an efficient way. A hydraulic ankle cannot move fast enough to be useful during sprinting and would slow down the runner. The use of hydraulics is also against current IPC regulations. Moreover, not all running blades are created the same, and some compress more during running. Are some prostheses better than others? Yes, but this is attributed to company standards and materials used. Two models of attachment are seen with RSP: Posteriorly and centrally mounted. Posteriorly mounted prosthetics attach to the back of the socket and act as a lever to help propel the athlete forward. This model is commonly seen in long jumping and springing blades. Centrally mounted prostheses are connected to the bottom of the socket and provide a more natural alignment to anatomy and comfortable feel. Both models provide amputees with different options to better utilize their running form and personal comfort.

Figure 5

Various Running Specific Prostheses Models

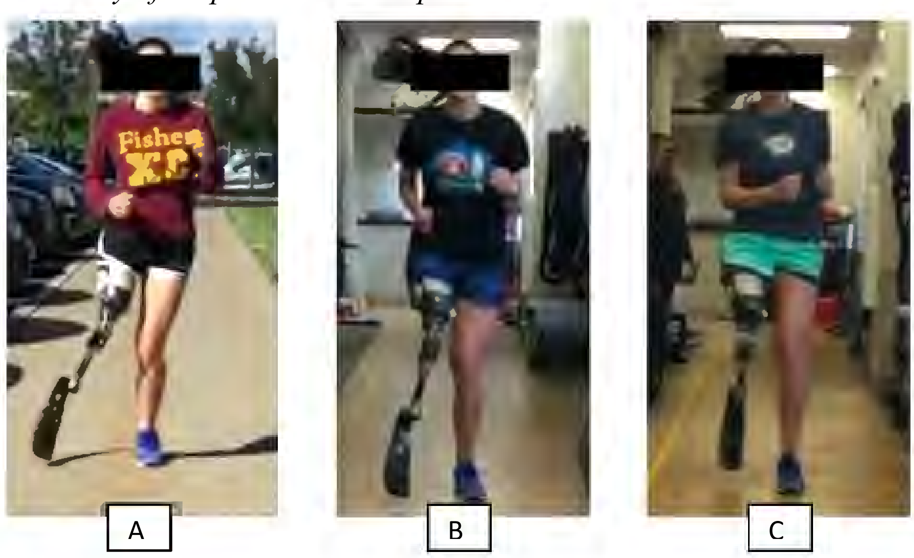
Note: Different models of Ossur Running blades: regular posteriorly mounted blade for sprinting, centrally mounted blade for running, and posteriorly mounted blade for long jump.

Additionally, regulations to ensure fairness are in place to prevent unfair advantages between amputee and able-bodied athletes on all levels. The MASH formula ensures that athletes do not have unrealistic proportions, such as stride length, to boost performance. Companies regulate stiffness based on the athlete's weight and height. With these rules and company standards, there is little to no room for cheating and a level competition field is maintained as each athlete's prostheses is inspected by professionals before competition. Moreover, placing athletes in their respective T61, T62, T63 and T64 categories is easy compared to other classifications, given that someone cannot fake or pretend to use a prosthesis. Overall, running-specific prostheses offer many benefits in energy efficiency compared to standard prosthetic models, and several types of prosthetic devices are designed specifically for competitive sports.

VI. Disadvantages of Running-Specific Prostheses

Running-specific prostheses have disadvantages that affect the athlete's body alignments, force generations, and muscle groups. Physical implications for amputee athletes can be strenuous due to imbalance and asymmetry causing physiological strain. Asymmetry is a common issue for amputee athletes. Running-specific prostheses are made to be 3-8% (4) longer than a biological leg to compensate for blade compression. The percentage is usually equal to a few centimeters. RSP weigh next to nothing compared to a biological leg, which is usually ⅙ of a human's body weight. Especially in cases of unilateral amputations, this creates an imbalance between the left and right sides of the body. This is not good because it creates unequal energy generation and displaces body torque, or the body's rotational force, which results in a lagging or choppy effect seen when these athletes run because one side of the body overcompensates for the other. Asymmetry can also lead to poor physiology and running mechanics. The muscles are being used in ways that are unnatural and can eventually wear down the muscle causing pain over time.

Figure 6
Case Study of Amputee with knee pain



Note: A college athlete's progression of hip strengthening after presenting chronic knee pain. (A) shows poor symmetry and uneven hips and shoulders. The affected leg swings around instead of driving through the knee while the unaffected leg lands central. (B) shows improvement with unaffected leg making contact more laterally. (C) shows forward knee drive, distinct use of both body planes, and equal hips and shoulder (23).

Lower ground reaction forces impact how running-specific prostheses work and lead to slower performances. Some argue running blades act as a spring and provide an unnatural, fast stride length. The prostheses do act as a spring, similar to how biological legs act as a spring. Running-specific prostheses cannot generate mechanical energy and rely on the user and other external forces to generate energy through movement. Ground reaction forces (GRF) are an important part of running. Studies have shown that amputees average approximately 9% less stance average vertical GRF for an amputated leg compared to a non-amputated leg across many speeds including top speed (7). Also, at the beginning running-specific prostheses cannot generate energy independently and rely on external forces to generate energy; therefore, at the beginning of a race, or take off, it takes amputees longer to reach top velocities than able-bodied athletes. It takes a few steps to produce the maximum forces necessary for springing at top speeds. This delay is unfavorable because it leads to slower times since it takes longer to reach the athlete's top speeds. Another aspect is how much energy is returned while running. Since a RSP replaces both the ankle and foot, its capabilities are limited when compared to them. The biological ankle can return up to 251% of energy while running while a running blade can only return up to 90% of energy (16). As a comparison, the running blade is working at one-third the compacity of a biological ankle. The prostheses return less energy because there are no muscles to absorb, generate, and release more energy. The human foot has 29 muscles and numerous tendons and ligaments which is why it can return more than what was originally put in.

There are technical limitations and dependency on RSP due to the risk of blade malfunction or breakage affecting performance. While running-specific prostheses are created from incredibly strong materials, they can break or snap if the blade is overused, has the incorrect stiffness, or is faulty. There are many cases where the runner's blade snapped or disconnected during a race. Hardware and connection to the running blade/socket can also be unreliable. In the 2023 World Athletics men's T64- 400m competition, USA's athlete, Hunter Woodall, was unable to compete due to a striped bolt coming loose during warmups. This made the entire prostheses unusable since the blade could not be reattached and no supplemental materials were available. Athletes are completely dependent on their socket and blade, so if an issue with the blade or fit of the socket occurs, it cannot be fixed quickly due to its complex design.

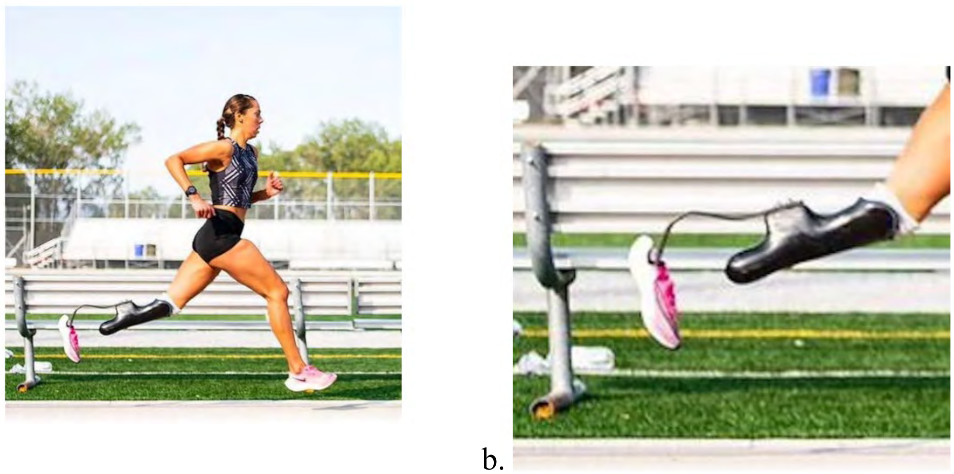
Another disadvantage of running prostheses is the lengthy complex process of acquiring and using them. There is a complex process of obtaining, fitting, and maintaining prosthetic limbs. The entire process of getting a prosthesis is long and difficult. Depending on why the amputation occurred, recovery can take between four to eight weeks or longer. After recovery, there are months of physical therapy and adjustment to moving in a prosthetic limb. A single running-specific prostheses can cost up to $35,000 and insurance often does not cover these blades because they are deemed nonessential. There are many organizations that help raise funds to provide running-specific prostheses; however, it is a process that requires time, patience, and hope. Furthermore, the prosthetic socket is not flexible and might change with time and training. Muscle growth or loss can alter the fit along with natural body changes. The blade itself will wear out over time and lose its ability to return energy, which would require an entirely new blade. This process is like breaking into new shoes, except it is their leg. Finally, the make of each blade varies from company to company. Today, there are well over 15 types of running blades that each have a unique build. Most people are not able to try every option to see what prosthesis is best for their condition.

Another disadvantage is how RSP affects the body, especially certain muscle groups. Overuse of specific muscle groups leads to potential injuries that are more common when using running blades. Overuse and specific muscle group weakness are a problem for these athletes. The hip flexors and quadriceps are frequent problem areas for amputees because these areas are now responsible for generating energy for the entire limb. Without an ankle joint, the knee and hip joints must compensate for up to four times the energy than non-amputated leg. Back problems are also common due to imbalances. Scoliosis can develop if uneven prosthetic legs are worn during early development or for a very lengthy period. It is important to address the muscle groups involved to strengthen hips, lower back, and overall balance. Furthermore, limitations in equipment access and difficulties in training with prostheses. Training to use running-specific prostheses can be difficult and time consuming, especially later in life. Depending on the amount of residual limb training can affect how strong or weak the remaining muscle groups are. Additionally, training can affect the size of the muscles which can change the room for socket fits. For example, if an athlete's weight fluctuates, they might need an entirely new socket to fit securely and safely, which could delay training. Furthermore, not all equipment is accessible for amputees. Shoes are not meant to be put on running blades, which removes the option to train on treadmills and other cross training because carbon fiber could destroy the rubber surface. If shoes are put on a blade, it is not completely safe, and the height can be affected. Amputees have a challenging time weight training resulting from issues with missing muscle groups and balance.

Amputees must develop different running biomechanics to run efficiently without pain or discomfort.

Figure 7

Example of shoe modification on prostheses for competition



a. b.

Note: a. Grace Norman (USA Paralympian in Triathlon) with a modified running shoe on her running-specific prostheses during training by Kendall Yates. b. Zoom in modified shoes and prostheses. (24)

Additionally, running blades force athletes to train and use equipment differently. Finding strength workouts, especially for the lower body, that athletes can use without an ankle or knee joint requires research and trying many options. Not all running blades are created to be used on all surfaces. Some running prostheses require a custom or hand-altered shoe to match the user's height and running requirements. Overall, there are many disadvantages involved in using running specific prostheses.

VII. Similarities in Athletic Performance

Many factors are neither an advantage nor disadvantage and are indifferent or incomparable. Studies show comparable metabolic rates between amputees and non-amputees and no significant difference in VO_2 max rates, metabolic rates, and blood volume. VO_2 rate depends on training and the athlete's ability to utilize oxygen during performance. The use of a running blade does not seem to affect this process. While it might be more difficult to train to build up VO_2 max rates, it is not directly altered by using running-specific prostheses. Additionally, metabolic rates have not been observed in studies to be significantly different. While the type of prosthetic can affect the metabolic rates of amputees to a small degree, metabolic rates are not different overall between amputees and non-amputees in a way that would affect performance. Moreover, amputation site and or side does not affect how an athlete performs with running-specific prostheses (7). Some researchers speculated because track athletes are under centripetal forces on the left side on a curved track, a left sided amputation would have an advantage; assuming that more forces are acting to further compress the blade and create more takeoff energy. However, in the study *Running-specific prostheses limit ground-force during sprinting,* showed that there were no significant differences in amputation location relative to velocity on track curves (7). Furthermore, blood volume is also important to consider. Theoretically, a lower blood volume due to an amputation could result in less cardiovascular strain during exercise; however, it could also lead to decreased oxygen delivery to muscles, potentially impairing performance (21,22). Blood volume is regulated by the excretory and circulatory systems, especially the renin-angiotensin-aldosterone system (RAAS) and can fluctuate to meet the body's needs (21). So, the body will adjust the blood volume to meet the body's requirements. This varies from athlete to athlete and is dependent on situational factors such as reason for amputation and how long since the amputation.

Running prosthetic devices do not increase or decrease injury risks as there are similar chances of injury between groups. While an amputee may not have to worry about rolling their ankle or getting a calf cramp, they do have to worry about other injuries. Having a prosthesis does not increase or decrease the chance of muscle related injury. While injury focus is not the same for amputees and nonamputees, there is still a relatively equal chance of muscle or joint injury. Most injuries for amputees are related to the liner and socket fit. Blisters and abrasions are common due to the tight fit and rigidity of the socket. If one of these develops, the only way to let them heal is to not wear the prosthesis, which delays training and is a slow process. As mentioned previously, overuse also contributed to injuries related to stress fractures, muscle tears, and other common running injuries.

Running prostheses have regulation on height and stiffness is determined by athlete weight. Height is regulated so it does not affect the athlete's performance. If a prosthesis is made to unrealistic proportions, there is a chance that it could provide some advantage. However, running-specific prostheses height is strictly regulated by athletic governing bodies. Additionally, the running-specific prosthesis is already taller than the original biological leg so unrealistic lengths would be difficult to compete in. This would be most relevant in bilateral amputation, in the absence of both lower limbs. Overall, height could be used as an advantage; however, it is regulated, and an illegal height would probably be a hindrance overall. Furthermore, blade stiffness is monitored by the manufacturing company. Prosthetic manufacturers recommend prostheses based on subjective stiffness categories rather than performance-based metrics. The value of stiffness presents the blade's stiffness in kilonewtons per meter (kN/m). Companies categorize stiffness in accordance with the athlete's weight and intensity levels. If a running-specific prostheses is too stiff, energy cannot be returned. If the stiffness is lower than recommended, each loading step would take longer, could cost the athlete time, or break entirely. While a running-specific prostheses could be made to create an unfair advantage, it is against all rules and policies and is ineffective to the athletes' performance.

Fatigue is a common topic in this discussion. While an amputee may not feel a lactic acid burn where their prosthetic limb is, this does not mean that they are producing any less or not feeling a lactic acid burn. They may just be feeling it in a different place. Other aspects can create fatigue. If the liner or socket does not fit well, it takes extra energy to compensate for the residual limb from shifting or sliding. Additionally, amputees cannot feel where they touch the ground. This could be harmful since the athletes cannot feel terrain changes or uneven ground. Many amputees have a challenging time maintaining their balance since they do not have a heel or ankle for stabilization. Using a running-specific prostheses does not guarantee that the user will be able to run fast. Some people will say that amputees have an easier time getting to the professional level of running with new blade technologies. However, becoming an amputee runner is not easy as some believe. It is more than receiving a running blade and immediately becoming a Paralympian. Very rarely do amputees begin to run within a year of their amputation. Most amputee runners had amputations from an early age or were in incredibly good health when their amputation occurred; therefore, these individuals adapted quickly to prosthetic devices. Yes, there is not as much competition, but the process of becoming an amputee athlete is, on average, longer and more intensive.

VIII. Conclusion

The field of lower limb prosthetic design is growing with more representation and accessibility on higher levels of competition. Running blades have created a profound impact in athletics by allowing more athletes to compete. These prostheses provide users with numerous advantages including optimized biomechanics, turnover rates, and variety in model options. However, they have many drawbacks including risk of overuse, lower forces, and difficulty obtaining and using RSP. Running specific prostheses provide efficient mechanics while running and are regulated to ensure fairness across competition. However, they are deficient in how they physically affect athletes, technical limitation, and dependency. This topic is important to not only athletes, but all physically active people. There is no case where a perfectly able-bodied person chooses to amputate their legs so they can run faster, and there is no record an amputee athlete holds over a nonamputee. While the margin has become smaller over the past decades, most records are not close or there is not a category for those using prostheses. Lastly, further research and considerations for equitable competitions are crucial to expand this field. The question is this: could humans develop the technology to close this gap between running blades and biological limbs? Runners? There is no certain way to prove that an amputee could run faster or slower if they had biological limbs. In the future, the paralympic and Olympics could be combined. It is important to determine what is fair or not. There are many track events, such as the 1500m and longer, that amputees are not able to compete because no formal classification has been created. Overall, running-specific prostheses have created a major impact in athletics, including both advantages and disadvantages.

IX. Afterword

When examining this issue, it is important to understand that a prosthetic limb has nowhere near the capabilities that a biological leg has. Running blades are created solely for running and not for daily life. Furthermore, there is an extreme shortage of research for running blades because of the small sample size and difficulty performing the experiments. No two amputees are the same in their biomechanics, how their amputation affects them, and how long they have been running as an amputee. Like able-bodied runners, no two runners are the same. All these factors affect studies, which leads to inconsistent results or small sample sizes. Most researchers would agree that a lot of work is necessary for this field. Also, physiological factors and economic opportunity play a significant role for amputee athletes that affect performance and the ability to reach a high competition level.

References:

1. HOBARA, H. (2014). *Running-specific prostheses: The history, mechanics, and controversy*. バイオメカニズム学会誌，Vol. 38，No.2. https://www.semanticscholar.org/paper/Running-specific-prostheses%3A-The-history%2C-and-Hobara/7b2d2b8bc49e58711af08fbc5cdbad6aa5faa7b7
2. Mainguy, M. (2022, September 1). *The history of the Paralympic Games*. Paris 2024. https://www.paris2024.org/en/the-history-of-the-paralympic-games/#:~:text=1960,ceremony%20of%20the%20Olympic%20Games
3. *Tokyo 2020 - athletics - men-S-100-M-T64*. International Paralympic Committee. (2021, August 29). https://www.paralympic.org/tokyo-2020/results/athletics/men-s-100-m-t64
4. Zhang-Lea, J. H., Tacca, J. R., Beck, O. N., Taboga, P., & Grabowski, A. M. (2023, May 11). *Equivalent running leg lengths require prosthetic legs to be longer than biological legs during standing*. Scientific reports. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10175537/#:~:text=Prosthetists%20generally%20prescribe%20RSP%20height,standing1%2C5%E2%80%938
5. International Paralympic Committee. (2024, March 11). *World Para Athletics Rules and Regulations 2024*. World Para Athletics. https://www.paralympic.org/sites/default/files/2023-02/2023_02_24 World Para Athletics Rules and Regulations February 2023.pdf
6. Boston Athletic Association. (2023). *PARA ATHLETICS DIVISIONS*. Para Athletes Divisions | Boston Athletic Association. https://www.baa.org/races/boston-marathon/para-athletes/para-athletes-divisions

7. Grabowski, A. M., McGowan, C. P., McDermott, W. J., Beale, M. T., Kram, R., & Herr, H. M. (2010, April 23). *Running-specific prostheses limit ground-force during sprinting*. Biology letters. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC2865064/ (1rsp)

8. Martyna [@martynbiri]. (2021, December 27). [Photo of running blade alongside of a house cat's hind leg]. Retrieved from https://www.instagram.com/p/CYA-KXrpMOA/?igsh=MWRyNngwdmQzMHF1cQ==

9. Beck, O. N., Taboga, P., & Grabowski, A. M. (2016, December 14). *Characterizing the mechanical properties of running-specific prostheses*. PloS one. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5156386/

10. "Ground reaction force". Oxford Dictionary of Sports Science & Medicine, by Answers.com. Retrieved 2011-02-26.

11. International Paralympic Committee. (n.d.). *Paralympic Games - Results*. International Paralympic Committee. https://www.paralympic.org/paralympic-games-results

12. de Bruin, T., De Bruin, H., & Martel, G. (2015, August 31). *Terry Fox and the Development of Running Prostheses*. The Canadian Encyclopedia. https://www.thecanadianencyclopedia.ca/en/article/terry-fox-and-the-development-of-running-prostheses

13. McHugh, J. (2007, March 1). *Blade Runner*. Wired. https://www.wired.com/2007/03/blade/?pg=2&topic=blade&topic_set=++Oscar+P+article

14. Sara M. Lewis, Man, Machine, or Mutant: When Will Athletes Abandon the Human Body?, 20 Jeffrey S. Moorad Sports L.J. 717 (2013). Available at: https://digitalcommons.law.villanova.edu/mslj/vol20/iss2/12260% vs 90% stat (50)

15. Dyer B. The Progression of Male 100 m Sprinting with a Lower-Limb Amputation 1976–2012. *Sports*. 2015; 3(1):30-39. https://doi.org/10.3390/sports3010030

16. Czerniecki, J. M., Andrew G., and Carolyn M. "Joint moment and muscle power output characteristics of below knee amputees during running: the influence of energy storing prosthetic feet." Journal of biomechanics 24.1 (1991): 6367-6575.

17. Davidson, M. (2005, March 9). *Innovative lives: Artificial parts: Van Phillips*. Lemelson Center for the Study of Invention and Innovation. https://invention.si.edu/innovative-lives-artificial-parts-van-phillips

18. Beck ON, Taboga P, Grabowski. AM. 2022 Sprinting with prosthetic versus biological legs: insight from experimental data. R Soc. Open Sci. 9: 211799. https://doi.org/10.1098/rsos.21179917

19. Connick, M. J., Beckman, E., Ibusuki, T., Malone, L., & Tweedy, S. M. (2015). Evaluation of methods for calculating maximum allowable standing height in amputees competing in paralympic athletics. *Scandinavian Journal of Medicine & Science in Sports*, *26*(11), 1353–1359. https://doi.org/10.1111/sms.12586

20. Willwacher, S., Funken, J., Heinrich, K. *et al.* Elite long jumpers with below the knee prostheses approach the board slower, but take-off more effectively than non-amputee athletes. *Sci Rep* **7**, 16058 (2017). https://doi.org/10.1038/s41598-017-16383-5

21. Sharma R, Sharma S. Physiology, Blood Volume. [Updated 2023 Apr 10]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2024 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK526077/

22. Convertino V. A. (2007). Blood volume response to physical activity and inactivity. *The American journal of the medical sciences*, *334*(1), 72–79. https://doi.org/10.1097/MAJ.0b013e318063c6e4ga

23. Santer, J., MacDonald, S., Rizzone, K., Biehler, S., & Beiswenger, T. (2021). Strategies for Gait Retraining in a Collegiate Runner with Transfemoral Amputation: A Case Report. *International journal of sports physical therapy*, *16*(3), 862–869. https://doi.org/10.26603/001c.23671

24. Yates, Kendall. (2021) *One-Hour Workout: Grace Norman's "No Watch" Track Session [Photograph] https://www.triathlete.com/training/workouts/one-hour-workout-grace-normans-no-watch-track-session/*