Prosthetics and Orthotics International, 1986, 10, 129–134

Running patterns of transfemoral amputees: a clinical analysis

G. MENSCH and P. E. ELLIS

Physiotherapy Services, Henderson General Hospital, Hamilton, Ontario.

Abstract

The challenge of rehabilitating young, healthy transfemoral amputees may extend beyond the boundaries of teaching them to adapt to functional activities of daily living. The goal for several of these amputees is to participate and sometimes even compete in recreational activities, including running. These amputee runners require prosthetic adaptations as well as a comprehensive individualized training programme to ensure that their running is as safe and energy efficient as possible. To help amputees achieve this, clinicians must understand normal and prosthetic locomotion. This paper compares the biomechanical differences between walking and running in normal locomotion and analyses the running modes used by transfemoral amputees. The modified running mode achieved with the Terry Fox Running Prosthesis subjectively "looks" more energy efficient to the observer and "feels" more energy efficient to the user. These assumptions have yet to be confirmed or refuted by a rigorous scientific research study. An outline of the proposed physiotherapy protocol includes the familiarization, treatment, and training phases. Physiotherapists involved in amputation rehabilitation may not be commonly confronted with this level of patient expectation. It is their responsibility to give realistic guidance to these amputees so that they can safely and independently pursue their recreational running activities. This need can best be fulfilled by providing sound clinical advice which has been validated by research findings.

Introduction

The performance of athletic skills is enhanced by the development of an individualized training programme which will condition the body and minimize the possibility of sports injuries, and by the selection of appropriate prosthetic components. These considerations will assist the amputee in accomplishing the specific physical requirements unique to each chosen sport.

Many sports, such as volleyball and basketball, require running, stride-jumping or hopping on one leg. Mastering these skills presents problems for many amputees because of the sudden ground impact which causes stump discomfort. Some transtibial amputees compensate by cushioning the forceful impact, using excessive hip and knee flexion. However, transfemoral amputees are unable to do this. During running, they must deviate from the normal running pattern by using a hop-skip running cycle (Mensch and Ellis, 1984). When using the hop-skip method an extra hop with the sound leg is introduced into the running cycle.

To facilitate more natural, safe and energy efficient prosthetic running for these higher level amputees, one must understand the differences between the running and walking cycles, assess amputees running modes and relate these findings to the prosthetic and physical training requirements.

The characteristics of walking and running

In the normal, the main difference between walking and running is the leg support pattern.

Walking

Walking involves a period of double support, when the swing leg has reached ground contact and the support leg has not yet advanced into swing (Fig. 1, top). The stance phase entails 60% of the cycle and the swing phase 40% (Perry, 1967); Hughes and Jacobs, 1979; Inman et al, 1981; Vaughan, 1984). On the average, energy requirements are moderate, as most persons utilize a walking speed which is comfortable for their cardio-vascular system (English, 1981; Inman et al, 1981).

All correspondence to be addressed to Mrs. G. Mensch, Director, Physiotherapy Services, Henderson General Hospital, 711 Concession Street, Hamilton, Ontario, L8V 1C3, Canada.

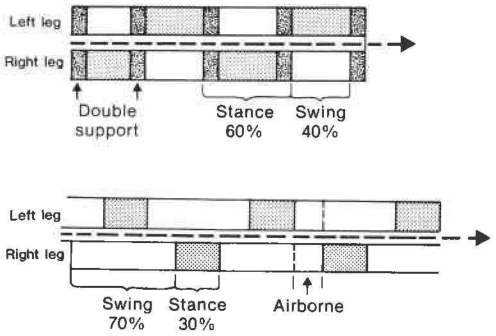

Fig. 1. Schematic representation of walking cycle (top) and running cycle (bottom).

Running

Running records an instant where both legs are simultaneously off the ground (Wells, 1971; Hughes and Jacobs 1979; Brody, 1980). This is the "airborne" phase which occurs following push off and ends with heel contact of the opposite leg. The increase in velocity during running results in a change in the distribution of time for stance and swing during the cycle. The running cycle then consists of about 30% stance phase and 70% swing phase (Fig. 1, bottom), and as well, the duration of the running cycle is shorter compared to the walking cycle (Brody, 1980; Vaughan 1984).

During running, step length, joint angulation and axial rotations increase. Joint angulations and axial rotations serve several functions during running. They—

- cushion the ground impact
- help to make running smooth and rhythmic
- decrease the vertical displacement of the centre of gravity thus contributing to energy efficiency (Inman et al, 1981; Man and Hagy, 1980)
- provide a balanced muscle length-tension and force-velocity relationship (Soderberg, 1983) thus assisting the forward acceleration of the body in the pushoff phase
- increase momentum.

Foot functions are enormously intensified during running, compared to walking. Heel contact occurs with forceful impact. Brody (1980) states that the runner "collides" with the ground. During mid stance the foot must hold the body over flexed joints and must provide a powerful pushoff to produce the main acceleration thrust. The intensified muscle work, needed for running, increases energy requirements (Inman et al, 1981).

The characteristics of walking and running—transfemoral amputees

Transfemoral amputees must adapt to—

- the functional loss of the knee, ankle and foot
- the unequal body weight distribution which results from the unilateral weight loss
- the initial disturbance in coordination and proprioception which affects balance (Mensch and Ellis, 1986).

When walking with a prosthesis they experience limitations in movement control and are acutely aware of the weight of the prosthesis. All of these factors affect the gait pattern.

Walking

Transfemoral amputees walk with an unnatural and stiff gait. This occurs because the natural axial rotation of tibia and fibula in relation to the knee and the foot is absent and because prolonged, active stump hip extension is required to maintain prosthetic stance stability (full knee extension) (Mensch, 1983). When compared to the position of the natural knee during the same phase within the gait cycle (slight knee flexion), the biomechanical difference and the effect on gait synchronization is evident.

Transfemoral amputees may adapt by demonstrating a variety of gait deviations and by keeping their energy output at a comfortable level by walking at a slower pace (English, 1981).

Running

For several reasons, amputees fitted with a standard transfemoral prosthesis are unable to use a normal running pattern—

- prosthetic heel contact is forceful and occurs without the support of the sound leg
- the ground reaction force responds with equal intensity to the impact and thus creates a strong prosthetic knee flexion moment (Fig. 2).
- the prosthetic knee is further forced into flexion by forward momentum
- the hip is unable to exert a sufficient extension moment to counteract prosthetic knee flexion

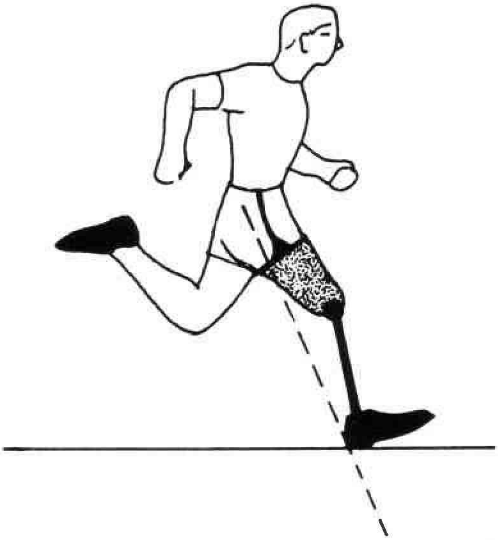

Fig. 2. Prosthetic knee flexion moment using 'normal' running pattern.

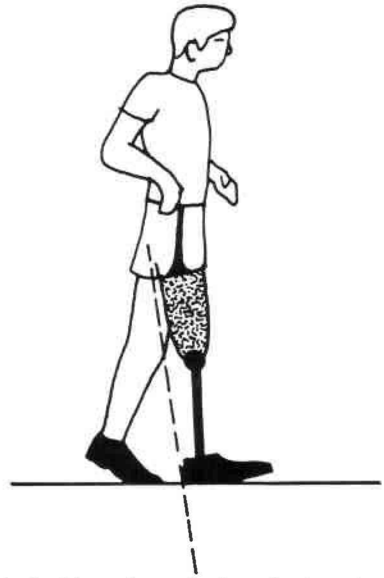

Fig. 4. Position of prosthesis at heel contact using hop-skip method.

Transfemoral amputees adapt by running with a hop-skip style. This cycle (Fig. 3) records a double stance phase (with the sound leg taking on an extra hop) and a prosthetic swing phase. The "airborne" phase occurs during the hop. There is a short period of double support when the legs alternate from stance to swing. The extra hop makes modified running possible. The hop occurs as a result of forward momentum and provides time to complete the prosthetic swing phase. This prosthetic swing may not be fast enough for running because forceful prosthetic pushoff can cause excessive heel rise which then results in a delay in swing completion.

The hop also decreases the distance between both legs when heel contact occurs (Fig. 4). The short period of leg double support, combined with the less acute angle of the limb at heel contact and the decreased impact at heel contact, permits controlled weight transfer to the prosthesis and reduces the intensity of the prosthetic knee flexion moment. The amputee is, thus, able to use stump hip extension functionally to continue running.

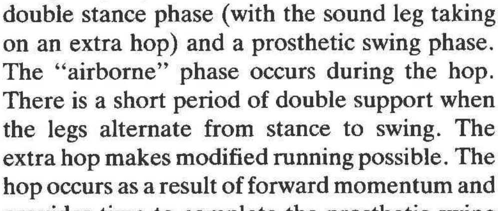

Fig. 3. Schematic representation of hop-skip cycle.

Running speed is produced by intense muscle work which is mainly generated by the sound leg and facilitated by excessive arm and trunk work. The running pattern is arrhythmic, abrupt and highly energy consuming (Inman, et al, 1981).

Running with a Terry Fox Running Prosthesis*

The components of the prototype of the Terry Fox Running Prosthesis (Fig. 5, left) include—

a flexible or a conventional quadrilateral suction socket with the addition of a Silesian band. This auxiliary suspension is necessary to reduce stump tissue rotation which, if present, can hinder running

a polycentric knee mechanism which provides stance and swing phase control

a precompressed heavy duty spring mechanism which, fitted into the shank section, absorbs ground impact and, temporarily, stores energy

a Greissinger foot, with, in addition to dorsiflexion, plantar flexion, inversion and

*Terry Fox, the first Canadian amputee cross-country runner, had the idea of fitting a telescoping mechanism into the shank of his prosthesis but, due to his untimely death, was unable to develop this idea further.

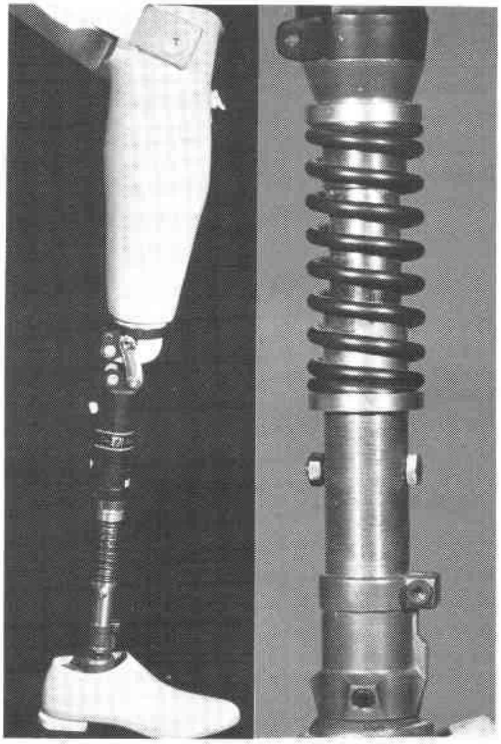

Fig. 5. Left, Terry Fox Running Prosthesis. Right, spring mechanism.

eversion, absorbs some axial rotation on weight-bearing.

The precompressed spring mechanism (Fig. 5, right), designed and developed by a team under the guidance of Guy Martel, a Canadian prosthetist, is the key prosthetic modification which allows transfemoral amputees to run with a near normal step pattern. The precompression of the spring mechanism is adjusted to the body weight so that during walking, it is inactive and only becomes operational during running.

When running, the spring mechanism compresses on heel contact. This cushions the ground impact and slightly shortens the prosthesis, providing stump comfort. Spring compression, maintained by weight-bearing as the support phase advances to mid stance, keeps the centre of gravity low. Stump hip extension is accomplished with more ease and the body is able to accelerate smoothly over the prosthesis. At the end of prosthetic stance, as weight-bearing decreases, the stored energy is released, propelling the prosthesis, at pushoff, into swing (Mensch and Ellis, 1984).

With this spring mechanism, transfemoral amputees are also able to hop on their prosthesis and to stride-jump. These two additional functional advantages give amputees a tremendous potential to participate in and enjoy many sports activities which previously were "off limits" to them. One distinct disadvantage, which has been identified, is the additional weight of the running prosthesis. Unfortunately the spring mechanism weighs 663 g.

One can hypothesize that the more normal running pattern, made possible with the Terry Fox Running Prosthesis, will reduce the amputee's energy requirements when compared to the hop-skip method. However the added weight of the spring component may adversely affect the amputee's energy requirements while running.

Although the subjective feedback from users has been very positive, it is felt that only a rigorous, scientific research study would demonstrate and validate the effectiveness of the precompressed spring mechanism on energy conservation during running.

Research considerations

The expectation was that this prosthetic design would permit transfemoral amputees to run in a more normal symmetrical step pattern.

During the analysis of running with this new prosthesis, several observations were made, leading to the following hypotheses.

1. The potential energy resulting from spring compression on weight-bearing is converted to kinetic energy as weight-bearing is decreased during the latter phase of stance. This released energy will intensify prosthetic pushoff, assisting the forward projection of the prosthesis into swing. This may possibly also help to raise the centre of gravity on the sound side.
2. The resultant normalization of the running pattern would decrease energy expenditure during running for transfemoral amputees compared to the hop-skip technique.

Physical therapy in the clinical trial (Fig. 6)

The physiotherapy component of the randomized cross-over clinical trial of the Terry Fox Running Prosthesis outlines the following possible hypotheses and protocols for the familiarization, treatment and training phases of the research study.

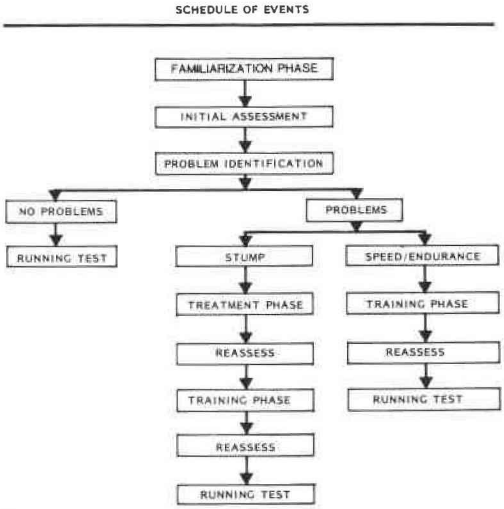

Fig. 6. Research project-physiotherapy schedule of events.

Familiarization

Although the subjects are prosthetic users, they will require an adjustment or familiarization period after being fitted with the test unit. The test unit consists of a transfemoral suction socket prosthesis with a Teh Lin* knee unit. The socket and knee unit remain constant but the shank sections, with and without the spring mechanism, are interchangeable. Both shank sections are equal in weight.

This phase will permit the subjects to adjust to the weight differential between the prosthesis that they are accustomed to wearing and the test unit. Problems may include tissue pistoning, altered proprioceptive feedback to the stump and difficulty converting to the functioning of the Teh Lin knee mechanism. The team will deal with any problems which may occur at the stump socket interface or with dynamic alignment to minimize, as much as possible, prosthetic factors which might hinder training.

The subjects will wear the test unit without the spring mechanism for three days, as this limb most closely resembles their existing prosthesis. They will then wear the unit with the spring for four days. The subjects will not run during this phase.

Treatment phase

The study subjects may have stump problems related to decreased strength, decreased range of movement, or problems related to skin conditions which may hinder training and consequently their ability to perform the running test.

*Trade name

The purpose of this phase is to minimize, as much as possible, these physical factors which might influence training. After specific assessment, appropriate physiotherapeutic intervention will be given until the subjects have optimal strength, range of motion and problem free skin. When this is achieved, the subjects will progress to the training phase. The treatment phase will be eliminated if none of the listed problems are identified during the assessment.

Training phase

Although the study subjects may not have any stump problems, they may lack the speed or the endurance to perform the running test. The test requires that each subject maintain fast walking or running at speeds 2, 3, 4, 5, 6 and 7 km per hour for three minutes each.

This phase will consist of supervised sessions progressing from walking to fast walking to jogging and, finally, to running. The ability to achieve and maintain the required speeds will be monitored weekly.

Each amputee's training will include equal time spent using—

- the test unit without the spring
- the test unit with the spring
- the test unit without the spring with weight adjustment (to compensate for the weight of the spring).

This will ensure that the subjects are fully prepared to perform the running test.

Using this schedule of events the subjects potentially could be training at different times but this should not pose a problem because once the required speed and endurance are achieved, the running test will be performed.

Training considerations

All amputee runners, like nonamputee runners require an individualized graded training programme (Fig. 7). Some common running injuries such as chondromalacia patella, (also called the runner's knee), tendinitis, shin splints and hamstring injuries may occur when athletes use incorrect running techniques, have poor postural habits, wear incorrect running shoes, omit warm-up and stretching exercises before running or are not properly conditioned (Brody, 1980).

Fig. 7. Running training.

Since all amputees rely heavily on the sound leg for balancing, standing and walking, it is vital to condition this limb.

Physical therapists must provide guidance regarding the type, intensity, duration and frequency of activity (Gibson et al, 1983) and must include resisted stump motion exercises in the conditioning programme.

Conclusion

The participation of many healthy adult amputees in recreational activities, including running, has increased the demands on the physiotherapeutic aspects of amputation rehabilitation. Physiotherapists must be able to provide realistic guidance to these athletes by continuing to observe and analyse the biomechanics of movement, participate in and incorporate research findings into the development and evaluation of prosthetic components for sports activities and formulate and evaluate comprehensive training programmes.

By meeting these requirements, physiotherapists will be able to continue to develop and maximize the potential of these amputee runners.

REFERENCES

Brody, D. M. (1980). Running injuries *Clin. Symp. (CIBA)*, **32 (4)**, 2–36.

English, E. (1981). The energy cost of walking for the lower extremity amputee. In: J. R. Kostuik and R. Gillespie (eds.), Amputation surgery and rehabilitation: the Toronto experience. New York: Churchill Livingstone, 311–314.

Gibson, S. B. Gerberich, S. G., Leon, A. S. (1983). Writing the exercise prescription: an individualized approach. *Phys. Sports. Med.* **11 (7)**, 87–110.

Hughes, J., Jacobs, N. (1979). Normal human locomotion. *Prosthet. Orthot. Int.* **3**, 4–12.

Inman, V. T., Ralston, H. J., Todd, F. (1981). Kinematics. In: Human walking. Baltimore: Williams and Wilkins, 22–77.

Mann, R. A., Hagy, J. (1980). Biomechanics of walking, running, and sprinting. *Am. J. Sports. Med.* **8 (7)**, 345–350.

Mensch, G. (1983). Physiotherapy following through-knee amputation. *Prosthet. Orthot. Int.* **7**, 79–87.

Mensch, G., Ellis, P. (1984). The Terry Fox running prosthesis. *Physiotherapy Canada,* **36 (6)**, 245–246.

Mensch, G., Ellis, P. (1986). Amputation levels.—stump characteristics and treatment considerations related to gait. In: Physical Therapy Management of Lower Extremity Amputations. Rockville: Aspen Systems Corporation.

Perry, J. (1967). The mechanics of walking: a clinical interpretation. *Phys. Ther.* **47**, 778–801.

Soderberg, G. L. (1983). Muscle mechanics and pathomechanics. *Phys. Ther.* **63**, 216–220.

Vaughan, C. L. (1984). Biomechanics of running gait. *CRC Critical Reviews in Biomed. Eng.* **12**, 1–48.

Wells, K. F. (1971). Locomotion: Walking and running. In: Wells, K. F., Luttgens, K. Kinesiology — The scientific basis of human motion (5th Ed.) Philadelphia: W. B. Saunders Company, 410–429.

FURTHER READING

Kumar, V. N. (1982). Normal locomotion and prosthetic gait deviation. In: Banerjee, S. N., (ed.), Rehabilitation management of amputees. Baltimore: Williams and Wilkins, 237–254.

Mensch, G., Ellis, P. (1982). Analysis of common gait deviations. In: Banerjee, S. N., (ed.), Rehabilitation management of amputees. Baltimore: Williams and Wilkins, 221–226.