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What can normal gait biomechanics teach a designer of lower limb prostheses?*

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Compensating a limb loss with prosthesis is a challenging task due to complexity of the human body which cannot be fully matched by the available technical means. Designer of lower limb prostheses wants to know what specification of the device could provide the best approximation to the normal locomotion. Deep understanding of the latter is essential, and gait analysis may be a valuable tool for this. Once prosthesis is built, gait analysis may help in comparing the wearer's performance with the new device and with the prior art, and in verification of the hypotheses being put forward during the development process. In this lecture, we will discuss some synergies of normal gait. We will focus on the required biomechanical properties of a prosthetic leg that can allow the prosthesis's inclusion in normal gait synergy without demanding excessive compensatory movements. We will consider contribution of leg joints to generation of propulsion for adequate design of lower limb prostheses especially those with power supply.

Key words: *biomechanics, prosthetics, anthropomorphicity*

1. Introduction

Compensating a limb loss with prosthesis is a challenging task: the complexity of the human body cannot be fully reproduced by the available technical means. Designer of lower limb prostheses wants to know what specification of the device could provide the best approximation to the normal locomotion. This essential knowledge can be aided by gait analysis: once a prosthesis is built, gait analysis may help to compare the wearer's performance with the new device and with the prior art, and to verify the hypotheses being put forward during the development process. In this paper, we will discuss some synergies of normal gait. We will focus on the required biomechanical properties of a prosthetic leg that can allow the prosthesis's inclusion in normal gait synergy without demanding excessive compensatory movements. We will consider contribution of leg joints to generation of propulsion for adequate design of lower limb prostheses especially those with power supply.

2. Contribution of gait analysis in a development cycle

The contribution of gait analysis to a cycle of designing the lower limb prosthesis is schematically depicted in Fig. 1. The order in which the blocks of the chart are positioned relative to each other may differ, depending on how the process is initiated. It may begin with a new hypothesis on a necessity to replicate in prosthesis certain gait characteristics. That would advice on a gait study with following specific gait parameters to verify if the hypothesis was solid. If the

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outcomes of the study are positive a set of design recommendations could be suggested for prototyping and further testing including the biomechanics study of an amputee subject gait wearing new prosthesis alternating with the existing prostheses. Results of such comparative study could show that the current prototype needs some modifications or even serious changes. In that case, a new development cycle should be initiated with corresponding gait analysis studies.

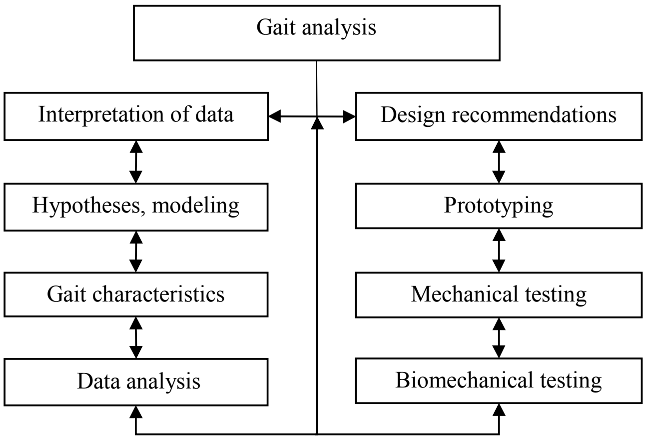

Fig. 1. Schematics of a design cycle for lower limb

3. Anthropomorphicity of lower limb prostheses

The entire history of prosthetics is driven by a desire for anthropomorphicity of the artificial limb. The designer uses a concept of anthropomorphism either consciously or intuitively in selecting the anatomical leg's features to be mimicked in prosthesis. The adequacy of this selection will be judged by the functionality and acceptance of the device by amputees. There is no common convention about a meaning of the term anthropomorphism when applied to specific situations including prosthetics. It is always a matter of perception and ability to deal with certain design characteristics of a product.

The traditional criterion of anthropomorphicity is "structural" related to a need for compensating the leg's shortening after amputation. Another criterion is "cosmesis" when visual, tactile and other anatomical characteristics are to be met. More criteria of anthropomorphicity came from biomechanics of locomotion in norm and with prostheses. In this paper, we will consider in more detail a *moment criterion* [1], [2] and how it was developed and verified by the gait analysis [3].

4. Pattern of the moment in the anatomical ankle joint

Any limb motion is a combination of rotations in the joints. Therefore the contemporary biomechanics as a science began with application of the moment concept to describe the relationship between forces generated by muscles and the resultant motions. This was first done by the Italian scientist Giovanni Alfonso Borelli, in a manuscript *De Motu Animalium* [4]. Borelli showed that the levers of the musculoskeletal system magnify motion, rather than force, and determined the position of the human center of gravity.

The "angle-moment" dependency in the anatomical ankle joint during the stance phase has a concave pattern (Fig. 2), indicating that the initiation of dorsiflexion meets small resistance, which increases nonlinearly to its highest level at the end of dorsiflexion. In Fig. 2, the stance phase is divided into seven consecutive events, beginning with "heel-on" event 1. In the interval between events 2 and 3, the first plantarflexion is completed, and the foot's sole is in full contact with the walking surface. Dorsiflexion then begins, and continues until event 5 "heel-off." The heel lifts, and rotation transfers from the ankle to rotation in the metatarsal joint (events 6–7). We will see further that this transfer utilizes inertia, and as such, is a component of ballistic gait synergy. The concave pattern of the moment's graph during dorsiflexion period suggests very small resistance to dorsiflexion in the beginning of the period (2–3), a fast increase of the resistance prior the "heel-off" (4–5), and a fast drop during the second plantarflexion (7).

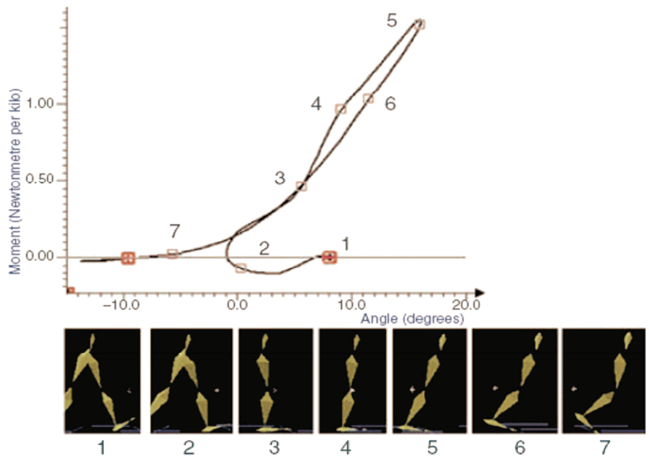

Fig. 2. Ankle moment as a function of the ankle angle in the norm. Events 1–7 correspond to consecutive phases of stance beginning with "heel-on" (Center for Human Performance, New England Sinai Hospital, Stoughton, MA). Reproduced from [3] with kind permission of Springer Science+Business Media

This sequence of events suggests that the major role of the moment in an anatomical ankle is to slow down dorsiflexion, and to lock the ankle joint facilitating the ballistic heel-off, but not to generate the body propulsion.

It seems logical to reproduce that anatomical "angle–moment" diagram in the prosthetic ankle joint by designing a construct whose resistance to dorsiflexion is substantially nonlinear with the slow rise and a jump-like increase when the joint has to be locked.

We will see further how prosthetic ankle with the "ankle–moment" diagram similar to those shown in Fig. 2 could be designed. First, we should examine if the anatomical ankle generates an active moment (torque) which is a source of propulsion for the body center of mass. That is a quite practical question directly affecting the specification for the prosthesis.

5. Whether the anatomical ankle generates propulsive "Push-Off"

The role of the anatomical foot and ankle in the generation of propulsion was investigated in many laboratories for purely scientific reasons and in response to rehabilitation needs. Since 1939 when they became available, force plate data have provided major objective inputs to understanding foot functioning. Analyzing the energy transfer during the stride, Elftman first presented a classic bimodal curve of the vertical ground reaction force [5]. He concluded that during the final stage of the stance period, the rest of the body received energy from the leg. That consideration served as the foundation for the theory of push-off as a major source for body propulsion.

Support for the theory of the major role of the ankle plantar flexors (*m. gastrocnemius* and *m. soleus*) in body propulsion during the second peak of the ground reaction force comes from the fact that the maximal EMG activity of *triceps surae* at push-off coincides with a greater increase in the total mechanical energy of the body. Also, the high power generated in the ankle exceeds that in the knee and hip joints [6]–[10].

In contrast to the "push-off" propulsion theory, there were studies that did not attribute propulsion to the ankle [11]–[14]. More researchers attributed the ankle plantar flexors with accelerators that facilitate the movement of the leg into the swing phase [15]–[17]. The study by Meinders et al. showed that during push-off, 23.1 J of energy was generated, primarily by the ankle plantar flexors, but only 4.2 J of this energy was transferred to the trunk. The authors concluded that the ankle plantarflexor's work is primarily to accelerate the leg into swing. They also suggested that the existing controversy in the role of the foot plantarflexion results from the multiple roles the foot plays in human locomotion.

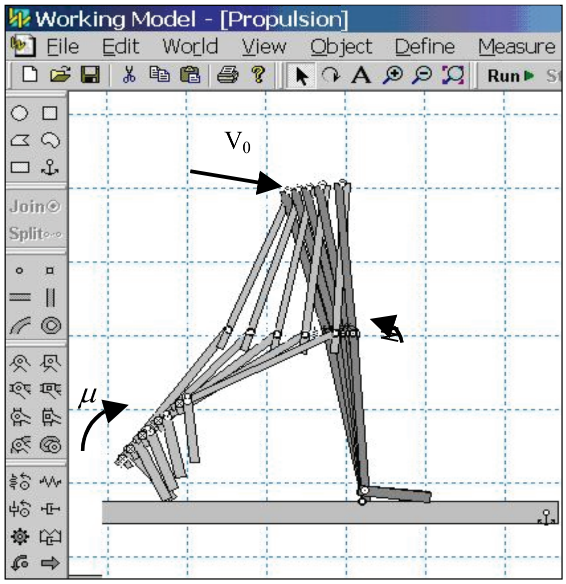

Fig. 3. "Working Model" simulation of the regular gait. Reproduced from [3] with kind permission of Springer Science+Business Media

As we showed in the comparative gait study and in the computer model [17], the flexion moment in the ankle can be propulsive only if the knee joint of the same leg is locked. Since in regular gait, the knee joint begins its flexion before the ankle starts its plantar flexion, transmission of the propulsive impulse to the body center of mass is limited, and the flexion moment in the ankle does assist in propelling not the center of mass, but the leg into the swing.

4.1. Simulation of propulsion in regular gait

To illustrate the ankle–knee synergy consider a computer model of propulsion in regular gait with Working Model[1] software. The model (Fig. 3) consists of two legs having three links (foot, shin, and thigh) each. The torque μ in the ankle of the trailing leg simulates the foot plantarflexion. The center of mass has an initial velocity V_0 acquired at the end of swing

[1] Design Simulation Technologies, Inc. Canton, MI 48187, USA.

phase of the forward leg. The knee in the forward leg has a passive rotational spring simulating the stance knee flexion/extension. Free rotation is allowed in the knee of the trailing leg, which provides ballistic stance flexion in the knee under gravity. Static moments of the limbs were taken to match the anthropomorphic data on the leg segments [18].

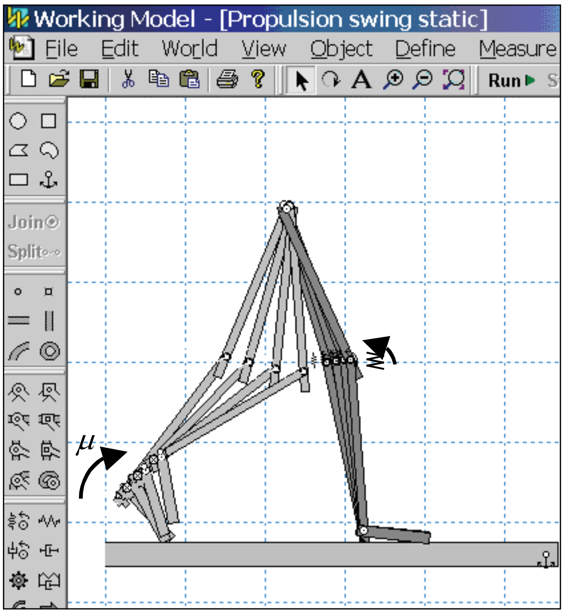

Fig. 4. "Working Model" simulation of the "push-off" event in static stage ($V_0 = 0$). The foot plantarflexion does not generate propulsion of the body center of mass. Reproduced from [3] with kind permission of Springer Science+Business Media

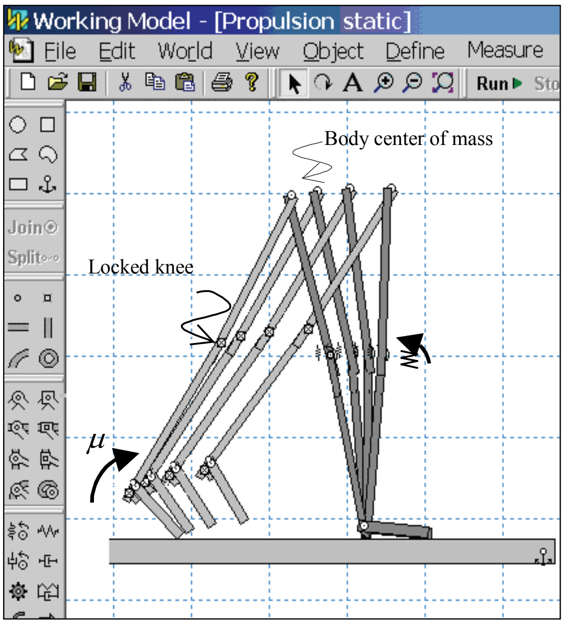

Fig. 5. "Working Model" simulation of the "push-off" event in static stage ($V_0 = 0$) with the locked knee in the trailing leg. Frames are shown at 0.05 sec intervals. Reproduced from [3] with kind permission of Springer Science+Business Media

The model kinematics resemble those of normal level walking with the center of mass moving forward and up after the foot plantarflexion. However, it remains not obvious what a primer source of propulsion of the body center of mass was. The uncertainty is caused by simultaneous contribution of the torque in the ankle of the trailing leg, and the presence of the kinetic energy of the center of mass with the velocity V_0. To resolve the controversy, we separated the action of the ankle torque and the center of mass kinetic energy in the following two models.

4.2. Computer simulation of propulsion in static stage

The model shown in Fig. 4 differs from the model of regular gait propulsion (Fig. 3) by zeroing the initial velocity V_0 of the body center of mass. All other model features are the same. The Working Model movie simulation begins with the torque μ acting in the ankle of the trailing leg. As seen from Fig. 4, the trailing leg is flexing in the knee and going to the swing similar to the regular gait model, but the position of the center of mass is not changing. That indicates that the push-off action alone in the trailing leg could not produce a body propulsion despite the plantarflexing torque having been applied to the ankle and the foot.

4.3. Computer simulation of intentional propulsion

The model shown in Fig. 5 simulates the human trial with the task of intentional propulsion with the predominant using of the torque in the ankle of the trailing leg. Its initial stage is static ($V_0 = 0$) as in model in Fig. 4, but in contrast to that, the knee in the trailing leg is locked. When the Working Model movie simulation begins, the trailing leg is transferring the impulse from the foot plantarflexion to center of mass. As seen from Fig. 5, the position of the center of mass is changing similar to the model of regular gait (Fig. 3).

4.4. Gait study comparing regular and intentional push-off

To develop compelling arguments in favor of, or against the push-off propulsion theory, we designed a gait study to compare propulsion in regular gait and in the gait with an intentionally exaggerated push-off by the trailing leg.

The vertical line (Fig. 6) defines the transition between stance and swing phases, and is approximately 60% of the stride time. Power in the ankle joint reaches its maximum at the end of stance phase (Fig. 6a). The ankle's power peak correlates to a decrease in dorsiflexion and transfer to plantarflexion. The fact that the power maximum coincides with the beginning of foot plantarflexion may be considered as an indication that the ankle is a generator of the propulsion push-off. However, it can be interpreted this way only if taken independently of the data on knee performance. If we add the performance of the knee joint to our consideration, we come to another result. Indeed, flexion in the knee begins simultaneously with the foot plantarflexion and even slightly prior to the plantarflexion. Since the knee is yielding, it absorbs the push-off impulse from the foot. Consequently, it cannot transfer that impulse to the body's COM, as opposed to the traditional belief [8]. Yielding of the knee when the foot is in plantarflexion can explain the low rate (approximately 25%) of transfer of power generated by the foot flexors to the trunk [16].

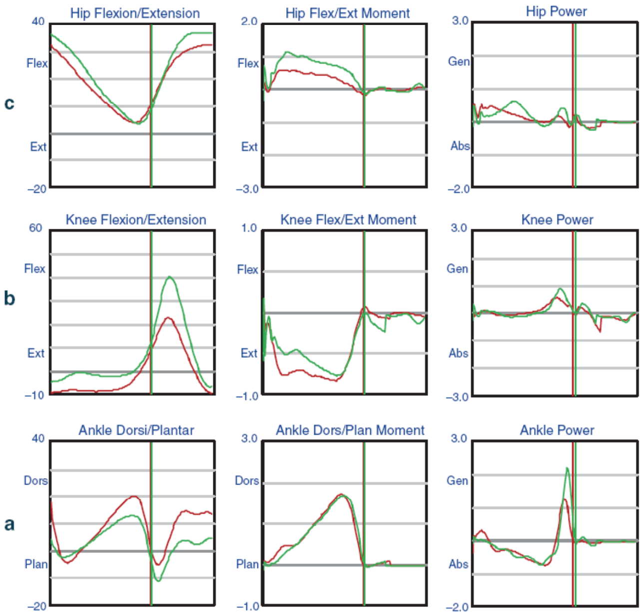

Fig. 6. Regular gait at self-selected speed and style. Flexion/extension angle, moment, and power in joints of left (red) and right (green) leg: (a) ankle; (b) knee; (c) hip. Reproduced from [3] with kind permission of Springer Science+Business Media

A reasonable question arises: if the foot plantarflexion (push-off) in the trailing leg does not generate the propulsion of the body, then how is the propulsion generated? We compared the moments in the knee and hip joints along with the vertical component of ground reaction. The comparison reveals that the peaks of both moments occur simultaneously at 10–15% of stride, coinciding with the first maximum of the vertical component of the ground reaction. That synchronous extension in the knee and the hip joints of the forward leg (Fig. 6b, c) provides the upward acceleration of the COM and is the major source of the propulsion as we suggested earlier[19], and as has been seen by other researchers [20].

The subject whose regular gait data are shown in Fig. 6, was instructed to walk while generating an intentional push-off with the feeling of his foot as the major actuator for propulsion of the body. By doing that, the subject reported an additional load to his calf muscles and an additional pressure on the forefoot sole. Kinematic and dynamic data (Fig. 7) show that compared to regular gait, the intentional push-off gait was associated with greater power in the ankle and with a locking knee of the trailing leg. The locking of the knee was not a part of the instructions given to the subject and occurred unintentionally.

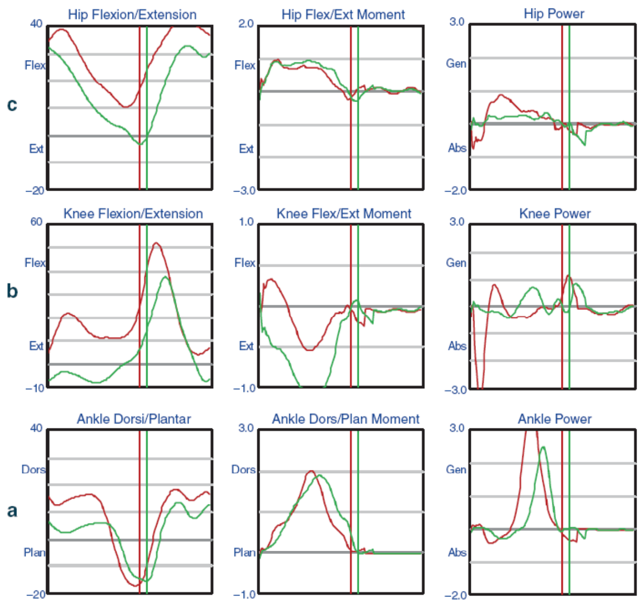

Fig. 7. Normal gait with the task of intentional aggravated push-off action of the foot. Flexion/extension angle, moment, and power in joints of left (red) and right (green) leg: (a) ankle; (b) knee; (c) hip. Reproduced from [3] with kind permission of Springer Science+Business Media

During the course of this exaggerated gait, the power maximum in ankle (Fig. 7a) was approximately 1.5 times greater than in normal regular gait

(Fig. 6a), and the timing of that maximum came noticeably earlier than in normal regular gait. Deceleration and termination of the dorsiflexion in ankle and the switch to plantarflexion also occurs noticeably earlier than in normal regular gait. The amplitude of the ankle angle and amplitude of the ankle moment are approximately 25% higher.

The increases in ankle angle, moment, and power indicate that the subject was able to generate a stronger push-off from the foot. Could one conclude that this push-off was indeed the source body propulsion? We believe that the answer should be affirmative because of the following arguments:

- The active flexion of the foot correlates with the locking of the knee joint in the extended position (Fig. 7b).
- That locking is produced by a moment whose value is noticeably higher than in normal regular gait (Fig. 7b).
- Therefore, the propulsive impulse is not cushioned in the knee, but is transferred to the body's COM.

5. Synthesis of a trochoidal mechanism of the prosthetic ankle

A nonlinear moment of resistance to rotation can be generated even with linear ties, if the rolling of contacting surfaces is employed instead of a single-axis pin joint [21]. In anatomical joints, epiphyseal surfaces of the bone heads in most cases, provide this type of cam rolling connection. Therefore, angulation in a joint can be represented as a rolling C_1 of the upper bone head along the bottom bone head, with the initial contact of the two surfaces at point C_1 (Fig. 8). Let the elastic tie of the initial length L_1 represent the muscle and ligaments, restricting the angulation (rolling). As a result of the rolling without the slipping of the upper bone, the two bones will contact each other at point C_2, and the elongated tie will be of length L_2 (Fig. 8). Moment M_2 of resistance to the rolling will be a product of tension in the elongated tie L_2 and the lever arm r_2. As was shown in [21], the second derivative of M_2 as a function of the angle of rolling will be positive indicating the pattern of the dependency "angle–moment" will be concave.

Analytic geometry recognizes a special class of curves with a common origin. A point, fixed to a body, which rolls along another body, generates them all (trochoids). The type of trochoidal curve depends on the shape and the relative orientation of both bodies and on position of the generating point relative to the circumference of the rolling body.

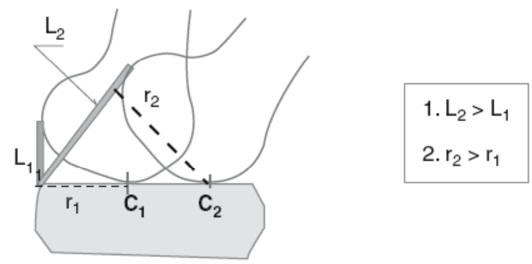

Fig. 8. Relative rolling of contacting surface in a joint: 1 – linear elongation of elastic tie; 2 – elongation of lever arm of the resistive moment due to rolling. Reproduced from [3] with kind permission of Springer Science+Business Media

To develop the parameters of the trochoidal mechanism of the prosthetic ankle, we solved the problem of the "accuracy points" synthesis of a planar joint [2]. The first Rolling Joint foot and ankle prosthesis with trochoidal mechanism [22], [23] was developed by the Ohio Willow Wood Company, Mt. Sterling, OH, under the name *Free-Flow Foot and Ankle*. The key feature of the prosthesis was a replication of the moment of resistance seen in the anatomical ankle. Three principal requirements were fulfilled in this design: relatively free articulation in the artificial ankle joint at the beginning of dorsiflexion, nonlinearly increasing resistive moment as a means for stopping dorsiflexion, and self-tuning to the speed of locomotion. The design achieved two goals of the prosthesis's functionality: minimization of pressures on the residuum, and normalizing the stance knee flexion in the uninvolved leg.

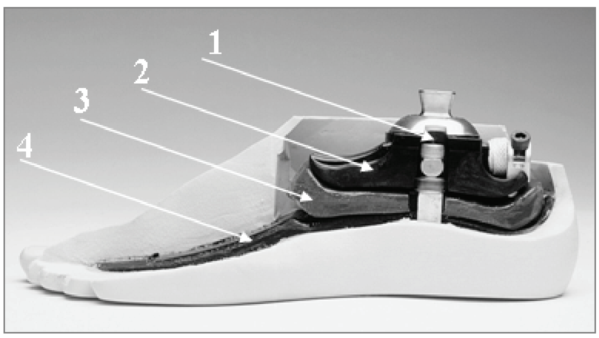

Fig. 9. Rolling Joint prosthesis *"Free-Flow Foot and Ankle"* by Ohio Willow Wood Co.: 1 – tuning screw for adjustment of initial stiffness; 2 – tibial surface of rolling contact; 3 – elastic cushion; 4 – base talar surface of rolling contact (courtesy of the Ohio Willow Wood Company, Mt. Sterling, OH). Reproduced from [3] with kind permission of Springer Science+Business Media

6. Long-term outcomes of rehabilitation with Rolling Joint Foot and Ankle

The more compliant knee mechanism in the Rolling Joint foot and ankle decreases the interfacial forces and pressures between the stump and the socket, normalizes the stance-bending of the anatomical knee in trans-tibial amputees, and improves symmetry in distant-time characteristics [24].

Fig. 10. A demonstration game of Standing Amputee Ice Hockey during ISPO 2004 World congress in Hong Kong. Reproduced from [3] with kind permission of Springer Science+Business Media

Positive feedback from the users of the *Free-Flow Foot and Ankle* promoted development of the Amputee Standing Ice Hockey (www.isihf.org). Long-term outcomes of rehabilitation with Rolling Joint prostheses were analyzed in ice hockey performance of amputee players [25].

7. Conclusion

Anthropomorphic prostheses should mimic the pattern of moments found in joints during sound gait.

Acknowledgements

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