Functional gait analysis of transfemoral amputees using Hydracadence® knee joints compared with other single axis prosthetic knees with hydraulic swing phase control.

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Abstract— **Hydracadence® is an original single axis prosthetic knee, which coordinates ankle and knee flexion. This study aims at comparing gait patterns of transfemoral amputees using Hydracadence® with, firstly patients using other knee joints without knee-ankle link, and secondly with normal gait. Eleven male transfemoral amputees are divided in two groups: six patients with the Hydracadence® joint (Group1) and five patients with other prosthetic knees (Group2). Twenty-three volunteers compose the Reference Group (Group3). Trunk, hip, knee and ankle motions are assessed with the 3D-motion-capture VICON® system. Knee moment is calculated via inverse dynamic method. In parallel, an original questionnaire assesses patients' activity and clinical background. A comparison of the values of the joints moments underlines that security is guaranteed during stance whatever the prosthetic knee. A kinematical study shows that during swing phase, hip sagittal motion is the same for Group1 and Group2. Vertical position of hallux is higher for Group1 than for both Group2 and Group3, so that foot clearance is facilitated with Hydracadence® knee. However, no repercussion is observed on the trunk lateral bending. The protocol proposed allows a complete functional comparison between components by combining clinical data with kinematic and kinetic information in the 3 planes.**

Keywords- foot clearance, functional demand, gait analysis, kinematics, kinetics, knee joints, transfemoral amputee.

I. INTRODUCTION

Gait patterns of transfemoral amputees change in comparison with normal gait. Since muscles are absent in the prosthetic limb, a substitute stabilization device has to be found during stance so as to avoid uncontrolled flexion. Besides, prosthetic knees have to allow and to control mobility between thigh and lower-leg during swing phase. Among all prosthetic knees, only one coordinates ankle and knee motions. Hydracadence® (Proteor, Dijon, France) prosthetic knee is a single axis joint with a hydraulic swing phase control system. A mechanical link between the prosthetic knee and the prosthetic ankle, which implies a dorsal flexion of the ankle when the knee flexes more than 20 degrees, is added in order to facilitate foot clearance.

Several studies have already been carried out to describe gait patterns of transfemoral amputees but only a few compares several prosthetic knees. [6,7,8]. The purpose of our study is to carry out a functional evaluation of the gait of transfemoral amputees using Hydracadence® prosthetic knees in comparison with others using single axis knee joints with a hydraulic swing phase control device but with no knee-ankle link. In parallel, prosthetic knee-joints functionalities are evaluated in comparison with asymptomatic gait. The objective 3D-kinematic and kinetic gait analysis underlines strategies chosen in response to security problems during stance phase and kinematic coordination between hip, knee and ankle motions during swing phase. Moreover, an original questionnaire is used to assess patients' activity and feelings.

II. MATERIAL AND METHODS

A. *Subjects*

Eleven male transfemoral amputees are considered during their clinical gait analysis examination and are divided in two groups. Group1 includes six patients using Proteor Hydracadence® prosthetic knee (mean age: 58.5 years, range 45 to 71 ; time since amputation: mean of 32.8 years ago, range 19 to 41). Only one of them uses one stick. Group 2 includes five patients using other single axis prosthetic knees also with a hydraulic swing phase control device but with no knee-ankle link. The age (53.4 years, range 34 to 71) and the time since amputation (34.6 years, range 11 to 56 years) are on average similar to the Group1. 23 volunteers compose the reference group called Group3, whose ages lay between 34 and 71 years. The mean age of the reference group is 50.9 years. All reference group parameters are expressed for the left side.

B. *Protocol*

The material and the experimental procedure is the same as the protocol described by Goujon [9]. In summary, kinematics and kinetics are collected respectively by means of an optoelectronic motion system (Vicon® 524, Oxford Metrics Ltd, Oxford, UK) and two force plates (AMTI® Advanced Mechanical Technology, Inc, Massachussetts, OR6-5). This

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protocol is completed by a questionnaire, fulfilled by a medical doctor, to evaluate the activity. Anthropometric measures of lower-limb (length and diameters of the foot, the shank and the thigh) are added to the protocol in order to assess joints moments according to inverse dynamic method.

C. *Data analysis*

Data are processed using specific programs, created by means of Matlab® (Mathworks, USA) software.

Kinematic and kinetic analysis

Joints kinematics is calculated using the methods described by Goujon [9].

The mechanical action exerted by the thigh on the leg is calculated with 3D inverse dynamic method, from the ground reaction forces and moments, by neglecting the inertial component. An anthropomorphic model is created from the anthropometric measures. It enables the calculation of the forces and the moments due to the weight of the leg, at knee joint, on both prosthetic and sound sides. The moment part of the wrench representing the action of the thigh on the leg is called "knee moment". The component of knee moment on the media-lateral axis, which generates a motion in the sagittal plane, is called "knee sagittal moment". To evaluate the action of this component at the beginning of stance phase, the area under sagittal knee moment curve is calculated between 10 and 20% of gait cycle. This parameter is called KA.

Questionnaire analysis

Patient activity is assessed by a scoring method (maximum score: 24) which takes into account the living (maximum score: 3), the job (maximum score: 7), leisure activities (maximum score: 9) and other displacements (maximum score: 9). The more the number of points, the more the inferred activity. Patients' activity is classed in one of the five categories proposed: poor (0 to 6), basic (7 to 10), average (11 to 14), important (15 to 18) and very important (19 to 24).

Among all the data, some parameters are selected to lead the comparison :

- Walking speed and activity score to evaluate global gait efficiency.
- During stance phase: sagittal knee motion and KA in response to security problems ; vertical and longitudinal component of the ground reaction force and ankle motions in order to evaluate how loads are transmitted through prosthesis.
- During swing phase: sagittal hip motion to show how prosthesis is actuated ; sagittal ankle and knee motions, foot clearance so as to describe lower-leg kinematics.

Statistical analysis

Significant differences between parameters according to Group1 and Group2 are evaluated with the Wilcoxon non-parametric test, particularly adapted to small groups (fewer than 8 subjects). Level of significance was set to p=0.05.

Relations between parameters are tested by an analysis of variance (ANOVA).

III. RESULTS

A. *Activity score and walking speed.*

Group1 has got a poorer activity than Group2 (10.5/24 and 14.4/24 respectively). It is confirmed by the average walking speed which is fewer for Group1 then for Group2 (1m/s and 1.1m/s respectively). The walking speed of patients from Group2 is close to the speed of able-bodied gait (1.2m/s).

B. *During stance phase*

Since the duration of the stance on limbs differs between the three groups, the following data are normalized during stance to be able to make a comparison between groups.

Security during stance

Sagittal knee moment generates extension of the Hydracadence® knee joint all along the stance phase. On the opposite, sagittal knee moment tends to flex the physiological knee at the beginning of the stance phase for Group3.

Among patients of Group2, several have a hydraulic knee brake (SNS system) so that stance is supposed to be more secured. Parameter KA is significantly more important for patients without SNS system(p=0,04), which means that the value of the moment must be higher for these patients to guarantee stability.

Loading on the prosthetic limb

At the beginning of the stance phase, the longitudinal ground reaction force (the opposite of the force exerted by the foot on the ground) corresponds to the loading on the limb. This component is significantly higher for Group1 (p=0,03), which means that patients of Group1 lean more on their prosthesis than patients of Group2.

Propulsion with the prosthetic limb

At the end of the stance, the longitudinal ground reaction force on the prosthetic limb, corresponds to the way the prosthetic foot pushes on the ground. This effort depends on the type of prosthetic foot. It is not possible to make a comparison between Group1 and Group2 since patients of Group1 use conventional feet whereas patients of Group2 are equipped with dynamic feet with a built-in carbon leaf system. We can only notice that the values of the longitudinal effort between Group1 and Group2 are, on average, very close.

C. During swing phase

Hip sagittal motion

Concerning Group1, hip extension on the prosthetic side is more important at the beginning of the swing phase but hip flexion is fewer on the prosthetic side at the end of the swing phase compared to the sound side. Besides, hip sagittal motion of the sound leg is close to the mean of the corridor of Group3, which represents 75% of the Reference Group population (figure1).

Amplitude of hip flexion-extension of the prosthetic side, in the sagittal plane, is the same between Group1 and Group2.

A relation is searched between the speed of hip flexion-extension and, firstly the type of prosthetic knee joint and secondly, the level of amputation, by means of an ANOVA. No relation is found with the type of knee (p=0.32) but there is a significant link with the level of amputation (p=0.03).

Pendular effect

Knee sagittal motion

Prosthetic knee joints flex progressively to reach a maximum at 70% of the gait cycle. No difference is observed between Group1 and Group2. Amplitude of knee flexion-extension of Group1 and Group2 is close to the one of Reference Group (figure2).

Ankle sagittal motion

The flexion-extension of the prosthetic ankle is very different for the three groups. While sound subjects plantar-flex the ankle, patients of Group2 keep the ankle in neutral position, and subjects of Group1 dorsa-flex their ankle (figure3).

Pelvic lateral motion

Pelvic lateral motion is the nearly the same for Group1 and Group2. However, contrary to the reference subjects, patients of Group1 and Group2 have a contra-lateral bending during swing phase (figure4).

Foot clearance

A significant difference between Group1 and Group2 is observed for foot clearance (p=0.019). In Group1, maximal vertical position of the hallux is higher on the prosthetic side ($mean_1$: 48 mm, SD_1: 11 mm) than on the sound side ($mean_2$: 32 mm, SD_2: 15 mm). Finally, the height of the hallux for the prosthetic side of Group1 is equivalent to the Reference Group ($mean_3$: 47 mm, SD_3: 8 mm).

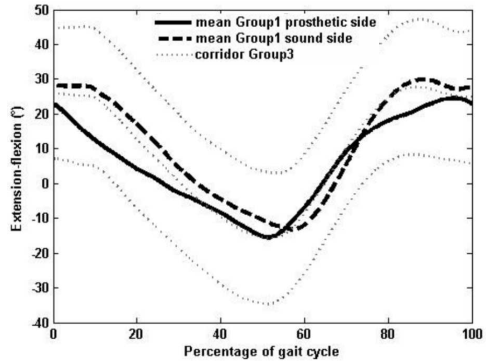

Figure 1. Hip sagittal motion: comparison between Group1 and Reference Group3 (positive: flexion, negative: extension)

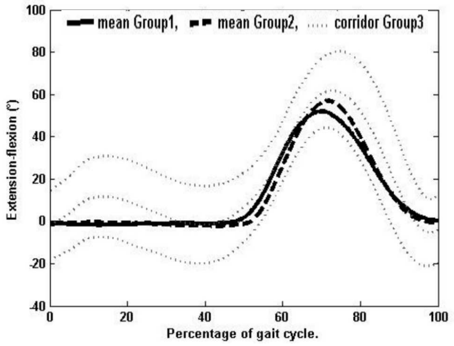

Figure 2. Prosthetic knee sagittal motion: comparison between Group1, Group2 and Group3. (positive: flexion, negative: extension)

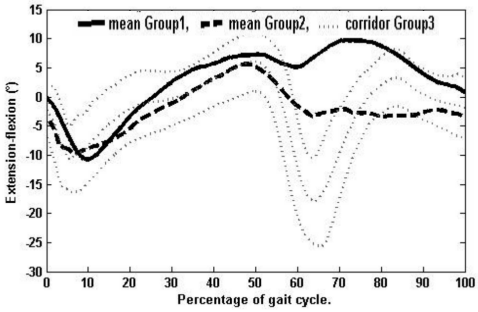

Figure 3. Prosthetic ankle sagittal motion: comparison between Group1, Group2 and Group3. (positive: flexion, negative: extension)

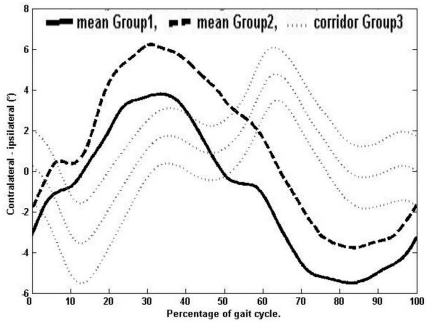

Figure 4. Lateral bend of pelvis: comparison between Group1, Group2 and Group3. (positive: ipsilateral, negative: contralateral).

IV. DISCUSSION

The purpose of this study is to evaluate Hydracadence® knee-joint functionalities by making a double comparison with other prosthetic knees and normal gait. Several authors have evaluated effects of prosthetic components without comparing the results with a reference group [2,4,8,7]. Besides, most of the studies which compare gait patterns of transfemoral amputees with normal gait, do not concern comparison of several prosthetic mechanisms [3,5]. Thus, the double comparison is an original protocol in the field of gait analysis.

A global study, considering age and time since amputation, seems not to be sufficient to describe the two groups of amputees. Indeed, it is useful to take into account not only the age but also the speed of walk and the activity. Besides, the results reveal relations between these three criteria but no general rule can be deduced from the data.

Our kinematic and kinetic gait analysis refers to functional demands that prosthetic knees are supposed to solve.

In response to the need of security during stance, the sagittal knee moment makes the prosthetic joint remains in full extension during weight bearing on the prosthetic limb. The value of this moment depends both on the value of the ground reaction force and on the position of the joint axis in relation to the direction of the force. On one hand, results reveal that the vertical component of the ground reaction force is the same for the two groups of amputees. Thus, the value of the force only depends on longitudinal ground reaction at the beginning of the stance, and this component is more important for Group1 than for the SNS systems of Group2. On the other hand, Hydracadence® system allows plantar flexion of the ankle at the beginning of the stance. It makes the prosthetic knee moving forward later, so that knee joint axis remains far behind the direction of the ground reaction. Thus, according to the value of the knee moment of extension, Hydracadence® prosthetic knees are safer than SNS systems. The study of the longitudinal component of the ground reaction force also reveals that Hydracadence® system allows an evolution of the direction of the force, close to normal gait. Indeed, between 10% and 20% of the gait cycle, longitudinal ground reaction force is more important for patients using Hydracadence® knee joint. We think it is due to the possibility of plantar-flexion of the ankle after heel-strike with the Hydracadence® system, which guarantees more stability.

During swing phase, the lower-limb motion is generated by the hip flexion. This flexion does not depend on the type of prosthetic knee joint. Boonstra [8] showed the same results, comparing mechanical with pneumatic swing phase control mechanisms. Nonetheless, hip flexion-extension depends on the stump length. Other studies refer to this correlation. In particular, Jaegers [3] showed that a person with a short or a medium stump length have a fast transition from hip extension to hip flexion.

The original knee-ankle relation of Hydracadence® prosthetic knees is noticeable during swing phase: when knee flexes more than 20°, ankle begins to dorsa-flex. The minimal vertical position of the hallux during swing phase is higher for patients using Hydracadence®. Thus, foot clearance is facilitated by the dorsa-flexion of the prosthetic ankle in comparison to other prosthetic devices. In comparison to normal gait, the ankle dorsa-flexion of Group1 at the beginning of the swing phase does not correspond to the normal extension but it avoids the fixing of the fore-foot on the ground. Moreover, at the end of the swing phase, dorsa-flexion is close to the one of Group3. Foot clearance is an important factor in particular when the patient walks on a slope, but, to our knowledge, no study has already taken it in account.

If foot clearance is facilitated for Group1, a repercussion on pelvis tilt should be noticed. However there is no significant difference between Group1 and Group2. An explanation is the lack of proprioception, which probably leads amputees to elevate their pelvis even if this movement is not necessary. A specific re-education could solve this problem.

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