Biomechanical analysis of pedalling for rehabilitation purposes: experimental results on two pathological subjects and comparison with non-pathological findings

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Abstract

In this paper the experimental results obtained by means of a prototype measuring device dedicated to the evaluation of the rehabilitation level of the lower limb are presented. The analysis of the experimental data collected on non-pathological subjects allows the identification of the characteristic meaning of the most significant parameters typical of healthy subjects. These data have been employed for a systematic comparison with the same parameters measured on two pathological subjects, in order to define quantitative indicators of the rehabilitation degree of the lower limbs and indicators of the "quality" of the movement.

1. Introduction

The aim of this research is mainly found in the medical field during the rehabilitation process. In fact in this situation the availability of a quantitative diagnostic tool is extremely useful for the evaluation of the rehabilitation level of the lower limbs. Moreover the system described here finds a possible application also in sport-medicine and in cycling performance evaluation.

In previous works (1, 2) the authors have developed the design of a machine for the biomechanical analysis of pedalling. The prototype design has been divided into two parts: in the first part, the whole biomechanical system has been modelled by means of an elementary scheme consisting of an articulated system with rigid links. In the second part, a special measurement device, that allows the kinematics and dynamics of the model to be solved, has been developed.

Several tests have been carried out on both non-pathological and pathological subjects, in order to obtain results that can be represented in a clinical manner. In a previous paper (3) the analysis of the experimental data collected on non-pathological subjects has been presented. By means of this analysis, the characteristic behaviour of the most significant parameters typical of healthy subjects has been identified. In this paper the same parameters measured on pathological subjects are analysed, in order to define quantitative indicators of the rehabilitation degree of the lower limbs.

2. The Biomechanical Model

The biomechanical model of the lower limb-crank is made of a five bar linkage and presents 2 d.o.f. for each lower limb (Figure 1).

The kinematic model has the following inputs: length of the link-segments; crank rotation angle ε_3, measured by an encoder connected to the central movement of the bicycle; angle ε_2 between the crank and the foot, measured by an encoder mounted on each pedal; ε_4, which is fixed and equal to 180°. The closure equation of the kinematic model allows calculation of the outputs of the model, i.e. the angles ε_1 and θ. Note that θ is the "hip angle", whereas the internal "knee angle" is kinematically calculated as: ε_1 - 180° - θ (see par. 4 and Figure 2).

By deriving twice the closure equation, it is possible to calculate the accelerations of each centre of mass of the link segments.

The dynamic model considers: mass-gravity forces; inertia forces; constraint reactions acting at the centre of pressure and measured by the load cells placed in the pedals; moments produced in correspondence of the joints by muscular activity.

This model is based on the following hypotheses (4, 5, 6): the mass of each link-segment is concentrated in its centre of mass; the position of each centre of mass relative to the link-segment is constant; the joints are modelled as rotational joints with null friction; the inertia moment of each link-segment remains constant during the motion; the geometric dimensions of the link-segments are constant.

By considering separately the link-segments representing the foot, the leg and the thigh and by imposing the equilibrium on each link-segment, it is possible to determine the internal actions and the moments acting on each joint: hip, knee, ankle (1, 2).

3. The Experimental Device

The experimental device has been realized by modifying a commercial training cycling apparatus with two instrumented pedals.

A load cell, which allows the pedalling force to be measured, and an encoder, that allows measurement of the angle between the crank and the foot, are mounted on each pedal. The crank rotation is measured by means of an encoder which is connected to the central movement. A data acquisition system mounted on a PC allows the synchronous acquisition of the angles and the forces. In particular, the acquisition frequency during the experimental tests has been 5 kHz. A belt brake on the flywheel permits to adjust the braking moment in the range 5 to 8 Nm.

4. Synthesis of the Experimental Results on Non-pathological Subjects

A wide measurement campaign has been undertaken in collaboration with the “Dipartimento di Ergonomia, Fondazione Salvatore Maugeri, Clinica del lavoro e della riabilitazione”, in Montescano, Pavia.

The experimental tests have taken into consideration 12 pathological and 15 non-pathological subjects which have been informed about the purpose of the research and given their consent.

The age of the pathological subjects (2 females and 10 males) ranges from 19 to 56 years (mean 31.25 years), their height from 157 to 190 cm (mean 174.75 cm) and their weight from 60 to 105 kg (mean 76.58 kg), whereas the age of the non-pathological subjects (2 females and 13 males) ranges from 22 to 31 years (mean 26.13 years), their height from 164 to 191 cm (mean 176.60 cm) and their weight from 52 to 84 kg (mean 70.00 kg).

For each subject three test-cases with a duration of 15 revolutions and a braking moment equal to 5.2, 6.5 and 7.8 Nm have been considered.

For each test the following parameters have been analysed:

- forces applied on each pedal in the direction normal to the pedal, measured by load cells;
- angular positions of each link segment, measured by encoders or calculated by the kinematic model: the "ankle angle" is the angle formed between the foot and the horizontal line through the ankle joint (negative if the foot is "tip down" oriented), the "knee angle" is the internal angle between the thigh and the leg and the "hip angle" is between the thigh and the vertical line through the hip joint (Figure 2);
- moments acting on each joint, calculated by the dynamic model (see par. 2).

The analysis of the experimental data collected on non-pathological subjects highlighted the typical behaviour of these parameters in healthy subjects (3).

In particular, from the analysis of the forces on the pedals during the tests with a load moment of force of 5.2 Nm, it was noted that the maximum force in steady state conditions is about 200 N and there is no significant difference between the forces applied on each pedal when the velocity is low (e.g. 40 rpm). However, when the velocity is higher (e.g. 60 rpm), the force on one pedal is usually higher than the force on the other pedal (this difference is about 10%). The limb that exerts the higher force is normally the left one for right-hand subjects; this limb has a mainly “pushing” function during the pedalling, whereas the other limb has a mainly “coordination” function. This conclusion emerges by observing the force curves as shown in Figure 3, relating to five revolutions in steady state conditions (after the first five revolutions) for a single non-pathological subject.

Consequently, this difference exists also in the moments acting on each joint. In particular, the difference is amplified in the hip moments (Figure 4), whereas it is less relevant in the ankle moments (Figure 5) (3).

From the analysis of the angular positions of the pedals, i.e. the ankle angles, it was noted that the pedal related to the limb with the “pushing” function is mainly oriented in the “tip down” position (negative values of the ankle angles). Vice versa, the symmetry axis of the angular position related to the foot of the limb with the “coordination” function is near the *x* axis (Figure 6).

Table I reports a synthesis of the mean values of the angular positions of each link segment in the healthy subjects (see also Figure 2 for the definition of the angles).

TABLE I   Mean values of the angular positions reached by the link segments for healthy right-hand subjects (tests with a braking moment of 5.2 Nm).

Joint	Max extension (°)	Max flexion (°)	Range (°)
Ankle angle (right limb)	+20	-30	50
Ankle angle (left limb)	+10	-40	50
Knee angle (right limb)	+140	+60	80
Knee angle (left limb)	+130	+60	70
Hip angle (right limb)	+70	+30	40
Hip angle (left limb)	+70	+35	35

The considerations reported above are assumed as a basis for the evaluation and comparison of the behaviour of the same variables collected on pathological subjects.

5. Analysis of the Experimental Results on Pathological Subjects

In this paragraph, the analysis of the experimental results on two pathological subjects is reported. These two cases have been considered as the most significant from a clinical point of view by the medical team of the “Fondazione Maugeri”; for this reason, the authors have preferred to show a detailed analysis of the experimental results concerning only these two subjects instead of displaying a synthesis of the data relating to all the pathological subjects examined; the other cases are very similar.

The first case is a male, 36 years old, 190 cm high with a weight of 105 kg and has suffered an Anterior Cruciate Ligament (ACL) reconstruction operation on the left limb.

The second case is a male, 19 years old, 175 cm tall with a weight of 60 kg and has suffered a plaster treatment of a tibia fracture of the right limb.

5.1. Subject with Anterior Cruciate Ligament Reconstruction on the Left Limb

The results obtained from the tests on a subject during the central phase of his rehabilitation period after an Anterior Cruciate Ligament (ACL) reconstruction operation were analysed.

Generally, after this kind of operation, the patient suffers a muscular hypotrophy with related loss of strength. Part of the rehabilitation process is dedicated to the recovery of the muscle structure of the thigh.

One of the aims of this research is the identification of quantitative and qualitative indicators to evaluate the muscular activity during the rehabilitation process.

In order to compare the results on pathological subjects to the results on healthy subjects presented in section 4, the data related to the first ten revolutions of a test with a load moment of force equal to 5.2 Nm is reported.

5.1.1. Forces on the pedals

From the graph of the forces applied on each pedal (Figure 7) it is possible to note a significant difference between the right limb (healthy) and the left limb (injured), in particular during the steady state conditions. The measurements related to the first revolutions are not significant for this analysis; in fact, the first peak of force of the left limb is due to the starting manoeuvres, in which the left limb has to operate first. In steady state conditions, the maximum value of force is about 400 N for the healthy limb and 100 N for the injured limb.

Moreover, the force applied on the right pedal presents negative values. This fact is highlighted in the graph related to the eighth revolution, in which a comparison between this pathological subject and a healthy subject is presented (Figure 8). These negative values appear in the period in which the foot can exert a slight upwards directed traction force on the strap that joins the foot to the pedal.

5.1.2. Angular Positions of the Link Segments

In Figure 9 the graph of the ankle angles during the first ten revolutions of a test with a load torque of 5.2 Nm and an average speed of 60 rpm is reported. The x axis corresponds to the horizontal position of the pedal.

From this graph it is possible to observe that the left pedal is mainly oriented in the “tip down” position, which is characteristic of the limb with the “pushing” function. On the other hand, the behaviour of the right pedal is not symmetrical to the x axis, as we expect from the limb with the “coordination” function, but it is mainly oriented in the “tip up” position.

From this analysis we can conclude that the “pushing” function is retained even when the “push” limb is injured. The irregularity in the behaviour of the “coordination” limb is probably due to the compensation in term of force requested to this limb when the “push” limb is injured.

Regarding the functionality of the ankle joint, the plots in Figure 9 confirm that the patient does not suffer problems at this joint, since the range between the maximum and the minimum angular position of the pedals is about 50° for both limbs, as in the cases of healthy subjects.

The data related to the knee and the hip angles were found to be similar to those collected on healthy subjects, as expected since the pathology of this subject would mainly affect the ankle angle.

5.1.3. Joint moments

The graph of the hip moments (Figure 10) points out the considerable functional difference between the two limbs.

If we consider a non-pathological subject (Figure 4) the left and the right maximum positive hip moments are very similar. On the contrary, for a pathological subject, the difference between the hip moments of the two limbs is more evident: the maximum positive value of the moment acting on the right hip is ten times greater than the maximum positive value of the moment acting on the left hip. Similar but less evident differences can be observed also for the forces on the pedals (Figure 7).

We can conclude that the hip moment is a significant indicator for the evaluation of the muscular activity of the thigh. Since it is reduced after a traumatic event such as an ACL lesion, it can be assumed as an indicator of the invalidity/rehabilitation degree of the subject.

The muscular hypotrophy – or, at least, lower strength capability – of the examined patient is evident even in the graph of the ankle moments (Figure 11). In this graph we note that the right ankle moment is negative for values of the rotation angle of the crank between 45° and 90°. By comparing Figure 11 with Figure 8, showing the force on the right pedal, we can verify that the ankle moment is negative when the force on the pedal is negative.

5.2. Subject with Tibia Fracture on Right Limb

The experimental results are related to a subject during his rehabilitation after a plaster treatment of a tibia fracture of the right limb. Plaster treatment has the advantage of eliminating the risk of infection because there is no cut in the skin. The disadvantage is that the knee and the ankle are included in the cast which may increase the joint stiffness.

The rehabilitation after this kind of trauma is aimed to restore the functionality of the tibio-tarsic articulation by means of articular mobilization and muscle structure tonification exercises.

In this case, the aim of the research is the identification of quantitative and qualitative indicators to evaluate the articular mobility and the muscular activity of the traumatized limb.

In this paragraph, the data related to the first ten revolutions of a test with a load torque of 5.2 Nm are reported.

5.2.1. Forces on the pedals

From the graph of the forces applied on each pedal (Figure 12) it is possible to note that the force on the left pedal (healthy limb) is higher than the force on the right pedal (injured). The maximum value of force in steady state conditions is about 250 N for the healthy limb and 150 N for the injured limb. This difference is less relevant in respect to the pathological case above described and could be due to the relatively low pedalling velocity performed by this subject (26 rpm), which clearly shows reduced mobility of the tibio-tarsic articulation. In fact, at lower velocity, with the same load moment of force, a lower power is needed and therefore the force difference between the healthy and the injured limb is limited. Even in this case, the force applied by the healthy limb presents negative values (see also Figure 13).

5.2.2. Angular Positions of the Link Segments

The graph of the ankle angles (Figure 14) points out the different behaviour between the two limbs.

We note that the graph of the right ankle angle is quite symmetrical to the *x* axis, as we expect from the limb with the "coordination" function. This fact confirms that the "coordination" limb maintains its function even after a trauma.

Moreover, from Figure 14 it is possible to observe that the left pedal is mainly oriented in the "tip down" position, which is characteristic of the limb with the "pushing" function.

The range between the maximum and the minimum ankle angle is about 50° for the left limb, as in case of healthy limb, whereas it is lower than 40° for the right limb. This value highlights the mobility problems of the tibio-tarsic articulation.

5.2.2.1 Conclusions about the ankle angles

We can conclude that the range between maximum and minimum values of the ankle angle is an interesting indicator for the evaluation of the tibio-tarsic articular mobility.

In general, an abnormal articular mobility can be due to one of the following causes, or to a combination of them:

- injuries affecting the bone structure of the joint;
- injuries affecting the ligaments or tendons of the joint;
- injuries affecting the flexor or extensor muscles of the joint.

In this case, the reduced articular mobility is probably due to the plaster treatment which has limited the muscular activity of the flexors of the ankle joint.

The data related to the knee and the hip angles are similar to those collected on healthy subjects. There is however an anomaly in the maximum value of the extension angle of the left hip joint, which reaches 75°; and this is due to marked behaviour of the left pedalling in the “tip down” position.

5.2.3. Joint moments

The graph of the hip moments during a single revolution in steady state condition (Figure 15) confirms the considerations about the behaviour of the forces on the pedals (Figure 10).

In fact, during the pedalling, the largest contribution in the pushing is given by the thigh muscle. Therefore, there is a strong correlation between the force on the pedal and the hip moment.

The values of the hip moments are very low for both limbs, because of the relatively low pedalling velocity of this subject.

In this case, the difference between the values of the hip moments of the two limbs is not due to a muscular hypotrophy of the right thigh, but to a reduction in the muscular activity of the right thigh in order to avoid loading of the ankle joint. In fact, this difference is less relevant in respect to the case previously analysed (see Figure 12).

The behaviour of the ankle moments (Figure 16) confirms the reduced muscular activity of the traumatized limb.

6. Conclusions

In this paper the experimental results obtained by means of a prototype measuring device dedicated to the evaluation of the rehabilitation level of the lower limb are presented. The calculation of the moments acting on each joint is possible by means of the simple biomechanical model proposed by the authors.

The analysis of the experimental data collected on non-pathological subjects allows identification of the characteristics of the most significant parameters typical of healthy subjects. These data have been employed for a systematic comparison with the same parameters measured on two pathological subjects, in order to define quantitative indicators of the degree of rehabilitation of the lower limbs (forces on the pedals and moments acting on the joints) and indicators of the "quality" of the movement (angular position of the pedals compared to an appropriate reference level).

These indicators could be monitored in the patients after a trauma on the lower limbs in order to evaluate the "adequacy" of the rehabilitation treatment and the improvements in the articular mobility and the muscular activity of the traumatized limb during the rehabilitation process.

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