BIOMECHANICS OF SPORT REHABILITATION

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INTRODUCTION

Athletes are frequently injured due to the large stress present in most sport performances as well as accidents of different nature.

In most cases such lesions involve muscles, ligaments, joints, bones and often peripheral nerves, too.

In all these cases clinical treatments for restoring athlete's capabilities are applied: casting, immobilisation, surgical intervention, traditional and specific rehabilitation procedures.

In order to restore the impaired function as much as possible, at least three factors must be considered in the rehabilitation process:

- the possibility of using alternative neural mechanisms which can be activated despite the original lesion (neural compensation);
- the possibility of adapting the motor pattern at kinematic and dynamic level, including also the use of personalised devices (special shoes, casting, etc.) to allow the athlete to perform the motor functions (mechanical compensation) in the best way;
- the morphological modifications of the neural structure as well as of muscles, tendons and bone structures (biological plasticity).

In this frame, the traditional analysis of correlation between the localisation of the lesion and the deficit of function appears insufficient to obtain the maximum potential recovery, given a certain damage.

Only by taking into account a quantitative multifactorial analysis of the motor function in relation to the lesion and the expected recovery, optimal results could be reached from medical rehabilitation and retraining process [5, 6].

This implies several steps:

- a detailed functional evaluation of each patient;
- the identification of those mechanisms which could be activated by appropriate training and assistive devices;
- a continuous monitoring of the patient's progress and the consequent adaptation of training itself.

In this context, a detailed multifactor analysis, as part of a wider process of "rehabilitation diagnosis", assumes a central role.

METHOD

In order for quantitative gait analysis of selected motor performances to be truly clinically feasible for patients with moderately to severely disabilities, the camera configuration and marker placements must allow for the patient to walk with the use of assistive devices, the assistance of another person and/or free arm swing. Preparation of the patient must be simple to avoid fatigue or discomfort, yet allow for accurate 3-D kinematic calculations. An additional electromyographic apparatus which may be applied to the patient should not interfere with camera-visualisation of the markers. The protocol must allow for real-time confirmation of data collection while the patient is

still in the laboratory. Finally, the protocol must allow rapid data elaboration so that clinical reports can be prepared in a reasonable time.
Taking into account these requirements a protocol for clinical applications of gait analysis has been developed at the Bioengineering Centre in Milan, Italy [8].

LABORATORY CONFIGURATION AND HARDWARE

The general layout of the laboratory is illustrated in Figure 1. An optoelectronic system (ELITE, Bioengineering Technology Systems, Milan, Italy) was used to measure the three-dimensional coordinates of 1 centimetre hemispherical retro-reflective markers attached onto the subjects' skin, at a sampling rate of 100 Hz [2, 3, 7]. Four video cameras were used with two cameras placed posterolaterally on each side of the subject. The working volume, 2 meters in height, 3 meters in length and 1 meter in width, was calibrated using a precision grid consisting of 42 markers (5 rows by 7 columns) placed in three parallel planes 0.5 meters apart.

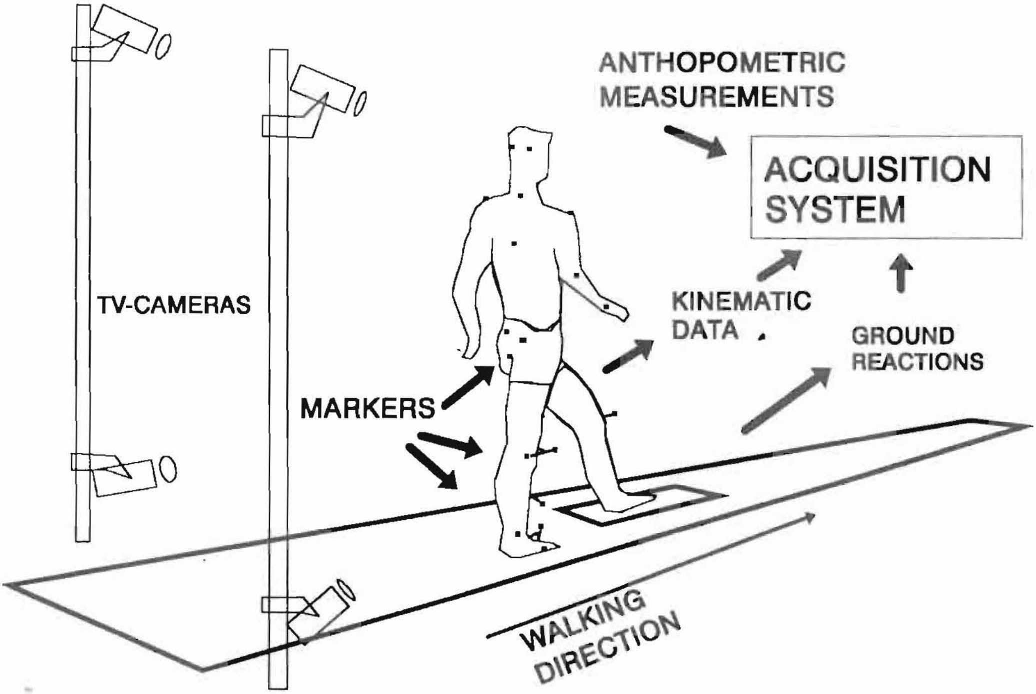


Figure 1.

Figure 1. The general layout of the gait laboratory: four video cameras were used with two cameras placed posterolaterally on each side of the subject; two force plates are staggered along the walkway.

The accuracy of the measure inside the volume was assessed, prior to each subject session, by measuring the distance between two markers connected by a stick that was moved in the whole calibrated volume. This measure was known a priori to be 200 millimetres. The difference between a priori and the measured distance was within 0.2

millimetres. Along time markers' coordinates were low pass filtered in the frequency domain by an algorithm that makes an estimation of the optimal cut-off frequency and minimises the residual noise in the signal. The resultant cut-off frequency was in the range of 3-7 Hz. Ground reaction forces were simultaneously collected at 100 Hz sampling rate using two force plates staggered along the walkway. The stride temporal phases were obtained from force platform data. In particular initial contact (IC) and last contact (LC) were defined as the sample times just before and just after the times at which the vertical ground reaction component became higher or lower then a threshold of 5 N respectively. Subsequent IC, occurring where there was no platform, was determined by analysing the markers trajectories and recognising the time in which they were superimposable to the previous IC.

PROTOCOL AND SUBJECTS

Several protocols have been developed to study specific and complex motor performances related to various specialities.

In the following the typical protocol "total body" adopted for complete analysis of locomotion is illustrated.

Each subject was prepared with markers placed onto the following bony landmarks: occipital region, C7, dorsal kyphosis, acromions, elbow, wrist, lower prominence of the sacrum, posterior superior iliac spines, lateral femoral condyles, lateral malleoli, and fifth metatarsal heads. Three additional markers on each lower limb were attached to the end of wands rigidly fixed over (a) the lateral femoral condyles, (b) the anterior tibial shaft, and (c) the forefoot. They will be referred to as the extended markers. For each subject the following general anthropometric measurements were taken: standing height, body weight, thigh length as the distance between the greater trochanter and the lateral femoral condyle, lower leg length as the distance between the lateral femoral condyle and the lateral malleolus and foot length as the distance between the heel and the great toe. The other anthropometric measurements, specific to the kinematic model, were additionally taken.

DYNAMIC ELECTROMYOGRAPHY

An 8 channels portable unit allows for measurements of the simultaneous EMG activity of 8 muscles by using bipolar surface electrodes with an incorporated preamplification to improve the signal to noise ratio.

The portable unit is connected to the central receiver and then to the computer by optical fibers.

The selection of the muscles to analyse depends on the clinical question. In most cases the following solutions are adopted: large muscles with a well defined function in the sagittal or in the frontal plane: at least two antagonistics for each joint of interest; four muscles for each leg if a comparison left/right is of interest.

DATA PROCESSING

All the above kinematic, dynamic and EMG data simultaneously taken on the patient during the same motor act are sent to the PC and processed by various programs. Some of them are based on mathematical models of the locomotor system and they must be fed with the relevant parameters defining the physioanatomical structure of the subject.

The main quantities which are computed in this way are:

- the time courses of angles at various joints (absolute values and projections on the main planes) (see Fig. 2) and several derived parameters like maximal extension, flexion or total excursion, etc.);

- linear and angular velocities and accelerations;
- time course of the 3 components of the ground reaction and the vector diagram representation including the center of pressure trajectory under the foot;

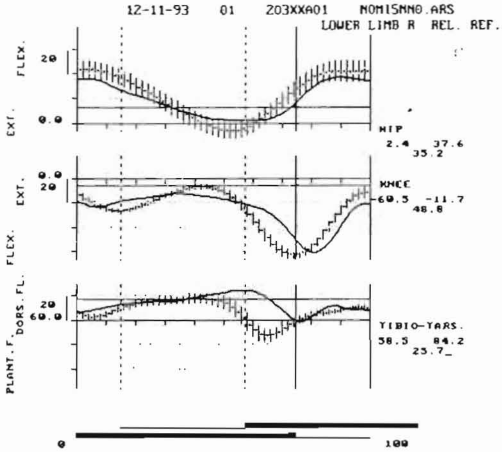
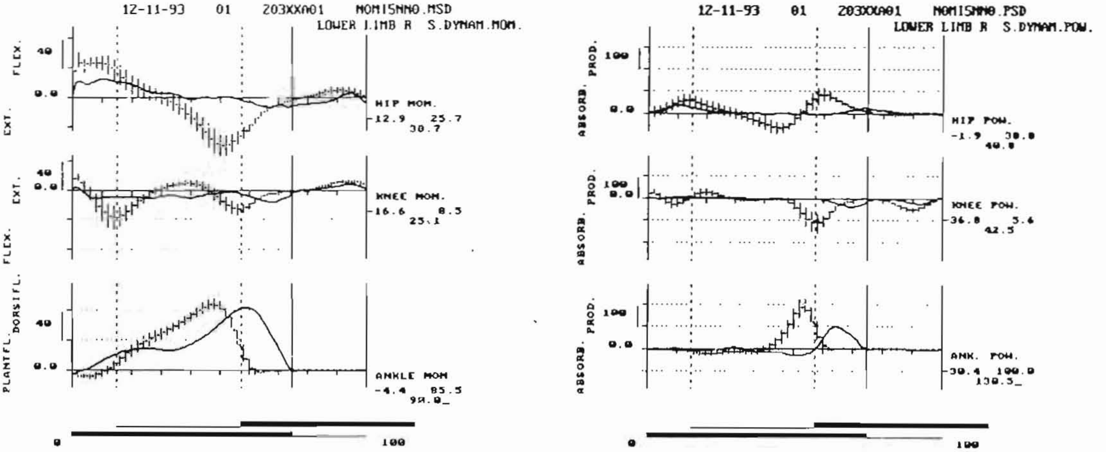


Figure 2. Time course of joint angles from a pathological subject compared with the curves of healthy subjects (mean value and standard deviations).



A

B

Figure 3. (a) Joint moments and (b) power at joints computed dynamically and compared with the curves of healthy subjects (mean value and standard deviations).

- the rectified, integrated and normalized EMG patterns of the investigated muscles compared with the temporal phases of the stride (stance, swing phase, double support);
- total moments at hip, knee and ankle joint giving important information about the muscle forces and role (see Fig. 3 A);
- power (see Fig. 3 B) and energy provided or absorbed at the same joints giving important information about the concentric and eccentric contraction of muscles;
- loads transmitted at various joints;

time courses of muscle lengths and velocities of lengthening or shortening during the locomotor cycle.

Special interactive programs have been developed for representing the above quantities by diagrams easily to read and to interpret from a clinical point of view. A predefined selection of the variables previously described are reported into the clinical record of the patient compared with the values "Typical of normality" so providing a general description in quantitative terms of each patient.

RESULTS

APPLICATION IN SPORT PERFORMANCE

A question of great relevance concerns how and when the complete motor recovery of the athlete has been reached. In fact the parameters which are normally used to assess the complete recovery of a normal subject are not sufficient to assess the recovery of a high level athlete, considering the complex mechanical demand which the musculo-skeletal apparatus must satisfy to reach the required performance.

In other words, after an accident, the motor recovery accepted for a normal subject can be absolutely inadequate for an athlete.

It is therefore necessary to identify new techniques to assess the efficiency of the rehabilitation procedures in the sport domain.

Recent technological developments make it possible simultaneous measurements and processing of a set of biomechanical variables related to kinematics, kinetics, and EMG activity during high level performance, so that the deviation from normality can be assessed, where *normality* is considered the reference pattern of the athlete when expressing a good performance and in the best shape.

Such a quantitative evaluation of motor efficiency in athletes is also important considering that in many cases of accident is difficult to differentiate the role of pure physiological deficiencies from the psychological ones which are often consistent in limiting the possibility of reaching results previously obtained.

In order to reach this goal, it is important to define suitable protocols to monitor the motor apparatus behaviour when performing selected exercises.

THE HIGH JUMP PROTOCOL

After an injury to the musculo skeletal system it is important to determine not only the static, anatomo-pathological aspects of such injury, but also its dynamic effects on the neuromuscolar function and on the capability to transmit loads through the joints (localization of the lesion). The primary choice to perform this kind of inspection is the selection of an exercise able to stress the motor apparatus in a way not so far from the usual sport activity. Moreover the athlete must be sufficiently familiar with the exercise, in order to execute it correctly and to be not interested by short term learning phenomena.

Vertical jump is a complex ballistic movement involving various energy release, storage and power flow mechanisms, in which the individual muscle groups operate collectively to produce patterned movements. Vertical jump is also an exercise largely utilized for field evaluation and, consequently, the majority of the athletes have not difficulty in performing it correctly. Furthermore this exercise requires a simultaneous involvement of the lower limb joints, that is an advantage if compared to other single joint devices, like dynamometers, used to measure biomechanical variables.

Usually the coaches take into account just the athletes' vertical displacements or several parameters derived by the ground reaction force (e.g. maximum vertical force, peak power, etc.). Even if these indexes of evaluation are important and commonly used, they are not completely adequate to monitor the motor coordination status as a function of training and rehabilitation programs. In fact the indexes provide a reasonable global evaluation of the whole performance, but they do not allow a disaggregated analysis of the single factors which contribute to the final result. Conversely, the analysis of joint kinetic variables have been demonstrated a powerful method to evaluate lower limbs motor patterns, to estimate joint mechanical loads, and to describe muscular functions [1, 4].

In the last ten years, the Bioengineering Center has been deeply involved in studying kinetic variables and biomechanical aspects of vertical jump exercises [9, 10, 11, 12, 13]. The results of these studies allowed to set up a protocol of evaluation that, to date, is routinary applied to athletes afflicted by impairments due to various injuries of the lower limbs.

The protocol is designed as follows: after 20 minutes of regular warm up, the subject is asked to perform 4 series of 5 two-legged vertical jumps, with the arms behind his back. No constrains are imposed on natural countermovement and the target is to jump as high as possible. The jumps are performed every 1 minute with a rest period of 4 minutes between the series. This sequence has been verified optimal, as to avoid the effects of the fatigue due to maximal muscular contractions, as to allow a consistent statistical analysis of the data. One foot at time is placed on the force plate and it is changed after the rest time between the series.

Five passive markers are apposed onto the following anatomical landmarks of both lower limbs: superior iliac spine, great trocanter, lateral femur epicondile, lateral malleolus, fifth metatarsal head.

The three-dimensional coordinates of the markers are measured by the ELITE System (BTS srl) operating with four TV cameras and a sampling frequency of 100 Hz. The ground reaction force is recorded by a Kistler 928 1B piezoelectric force plate at a sampling frequency of 500 Hz.

Net joint moments and powers of the limb on the force plate, are computed by means of inverse dynamic analysis. The software package SAFLO [8] is utilized to compute the aforementioned mechanical variables. As input the software needs also specific anthropometric data of the subject in order to estimate the 3-D coordinates of the internal joint centers through those of the anatomical landmarks of the legs. The regression equations proposed by Zatiorskji et al. [14] are utilized by the program to estimate mass, position of the gravity center, inertial moments and kinematics of each segment of the lower limbs.

Jumping height, joint angles, moments and powers are the variables usually analyzed to evaluate the movement. Statistical analysis is performed by considering the peak value of moments and powers. Data of each trial are accepted for the analysis only after a preliminary check of the jumping height distribution.

CASE ANALYSIS

As example of application of the method, will be discussed the data belonging to a first league rugby player, examined 16 months after a serious lesion of the anterior cruciate ligament of a knee. After the injury, the subject was surgically treated in order to rebuild the damaged ligament and, at the time of the experiment, he was regularly playing in his team.

In table I the mean values and standard deviations of the results are reported. In figure 3 and 4 are depicted representative curves of the sagittal joint angles, moments and powers of the healthy and injured limb respectively.

First of all it must be underlined that the data from left and right limb belong to consistent and comparable performances. This statement is due to the jumping height measures: the mean values are almost equal (similar performances), the reduced standard deviations ensure that fatigue did not afflict the motor action of the athlete.
The analysis of the data allows to make some inter and intra-individual comments.
Inter individual analysis has been performed thanks to the data recorded by a homogeneous group of 12 healthy rugby players.

	Healthy limb			Injured limb		
	Hip	Knee	Ankle	Hip	Knee	Ankle
Peak Moment (Nm)	154.4 (15.4)	107.3 (6.0)	141.8 (10.7)	111.4 (7.9)	69.8 (8.8)	127.8 (3.1)
Peak Power (W)	538.4 (60.1)	751.0 (94.1)	843.1 (139.6)	551.8 (29.0)	425.5 (35.1)	769.4 (58.6)
Jumping height (cm)	47.1 (1.7)			46.5 (1.3)		

Table I. Mean value and standard deviation of kinematic and kinetic variables, obtained by the vertical jumping analysis (ten jumps per leg). Data from a rugby player 16 months after the surgical intervention for the reconstruction of the anterior cruciate ligament.

The level of performance points out that the athlete is in a good physical shape. This is demonstrated by his mean jumping height placed inside the distribution of the sample and a little bit over the average. Than, if one consider only this result , the athlete may be defined "completely recovered".
Hip and ankle peak moments of both legs, normalized with body weight and subject height, are inside the sample of healthy players. All these moments, once those belonging to the ankle of the injuried limb are excluded, are larger than the average. Conversely, both the peak moments of the knees are below the values measured from healthy subjects, and the difference reaches a level of statistical significance. The lack is more pronounced in the injured limb (-50% of the average) than in the healthy one (31% of the average).
Hip and ankle peak powers are aligned with the normal values, maintaining the tendency to be over the average. Normal values are present also at the healthy knee but, as happen for the moment, the peak power at the injured knee is below the normality at a level of statistical significance (-41% of the average).
The amplitude of the peaks evidences compensatory mechanisms, that seems to be applied to support the reduced contribution of the knee joints by means of a stronger involvement of the other joint muscles groups. The addition of a further motor variable of control, namely the angular velocity, allows the subject to adopt kinematic patterns able to establish almost normal values of peak power at the healthy knee, while it is not sufficient to balance the power at the injured one. This inability may be related to the fact that the peak of power is reached when the knee joint is almost 20° far from his maximal extension (see figure 3 and 4) just when the anterior cruciate ligament begin to be involved in the final knee extension.
The intra individual analysis has been performed by comparing the data of the two legs. A large bilateral asymmetry is evidenced by hip and knee peak moments (30% and 35% respectively) and knee peak powers (43%). In all the cases the values of the

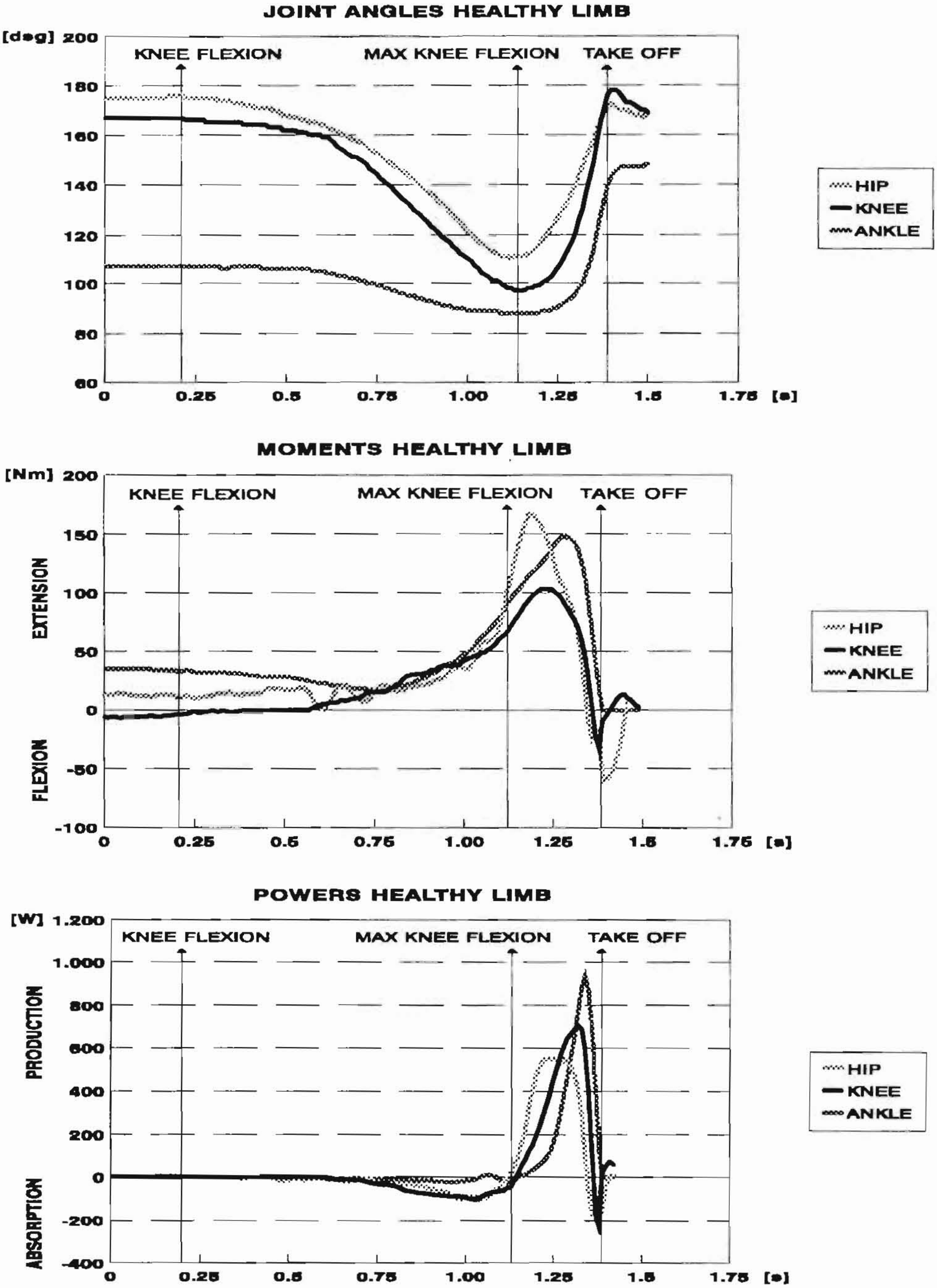
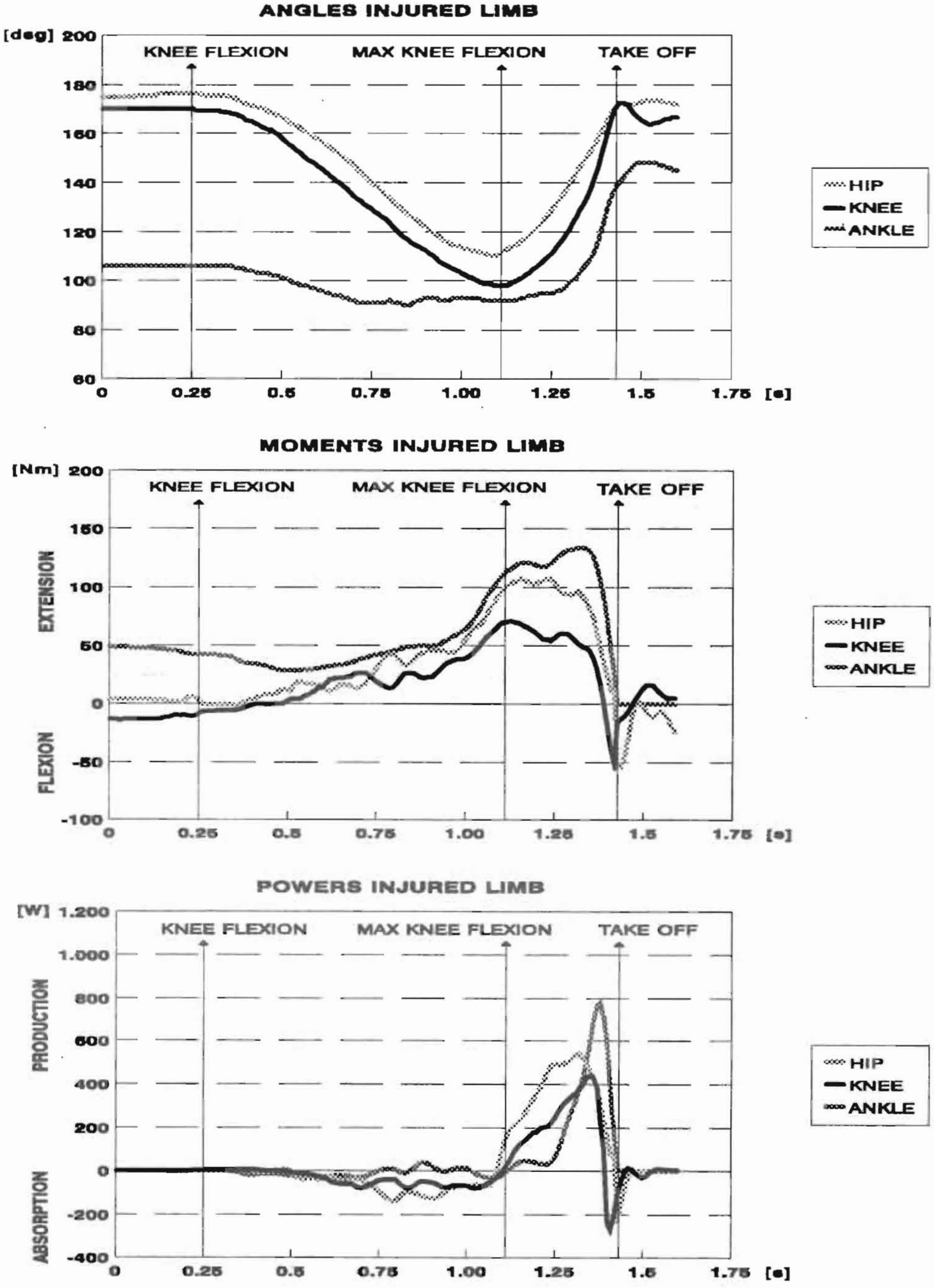


Figure 4. Representative joint angles, moments and powers measured during vertical jump on the healthy limb of a rugby player.


ANGLES INJURED LIMB

MOMENTS INJURED LIMB

POWERS INJURED LIMB

Figure 5. Representative joint angles, moments and powers measured on the limb surgically treated for anterior cruciate ligament reconstruction. The subject is the same of figure 4.

healthy limb are higher than those of the injured limb. The asymmetry of the moments is more than two times the averaged value computed on the reference sample [13], and more than three times for the powers.

Figures 3 and 4 allow to deepen the analysis of the individual non symmetric strategy adopted to perform an apparently symmetric exercise. Vertical jump is executed with the almost simultaneous flexion of the lower limbs joints, followed by their quick extension. The duration of the flexion and extension phases, shows that the athlete flexes faster and extends slower the injured limb than the healthy one. The differences in speed of flexion could be aimed at storing a larger amount of elastic energy during countermovement in the muscles of the affected limb, while the difference in speed extension could be devoted to adopt kinematic patterns useful to modifying and controlling the elastic and contractile energy release. Energy release control has a specific goal the reduction of knee moment and power (and consequently the loads acting on the joint) during the last 20° of extension, when the anterior cruciate ligament participates actively to the movement. The observation is confirmed by the curves of the moments that, on the injured limb, are flatter. Furthermore, in this side the athlete changes the well known proximal to distal strategy in reaching the maxima (hip > knee > ankle), by anticipating the knee maximum when the joint is at its maximal flexion, and the anterior cruciate ligament is not involved in the movement. Of course, the behaviour of the knee influences the mechanical action of the other two joints.

Similar consideration may be done for the power curves, even if in this case the proximal to distal strategy is maintained. The control of the angular velocity, allows the subject to establish normal peak values at the healthy knee, while it is not sufficient to balance the power output of the injured knee.

In conclusion it is possible to state that the athlete, even if he is recovered from a physical point of view, is far from a balanced and symmetric motor behavior.

He solves the problems related to vertical jump motor tasks by adopting kinematic and kinetic strategies aimed at reducing the load transmission through the injured joint without compromising the final performance.

At this point a serious question arises: what will be the long term effects on his musculo skeletal apparatus that is daily loaded by a heavy training and respond to the solicitations with asymmetric and compensative mechanical ouptuts?

The only reasonable answer is to promote a stronger co-operation among the biomechanicists, that can analyze the subjects, and the group of people that design physical and rehabilitative programmes in order to find new and personalized solutions.

CONCLUSIONS

In the last few years a significative number of athletes have been investigated at the Bioengineering Center of Milan. They presented several functional deficiencies due to different lesions of the musculo skeletal apparatus, involving muscles, joints, tendons and ligaments. All data have been stored in a specialized data bank.

First of all this activity has undoubtedly proved the feasibility of these investigations in a sport dedicated environment. They were well accepted by the athlete and not considered fatiguing or annoying and the results obtained in general have been proved to repeatable, robust, and consistent.

The information provided were valuable for the choice of the best training for improving the recovery, the prevention of secondary defects and the evaluation of the efficacy of the therapy and the rehabilitation procedure adopted.

A further exciting goal is the identification of individual "pathological " motor patterns which demonstrate how a specific lesion is inducing a "new control strategy" able to allow the desired performance. The learning and adaptation process involved are of great potentiality to suggest new rehabilitation procedure.

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