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Knee Orthopaedic Device
How Robotic Technology Can Improve Outcome In Knee Rehabilitation

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***Abstract*— Following knee injury or surgery, knee rehabilitation therapy is an essential step to recover normal joint function for daily activities. Physical rehabilitation can take several weeks or even months until full range of motion and joint flexibility are regained. Knee rehabilitation will lead to satisfactory results only at the condition that exercises are performed regularly. An important part in knee rehabilitation is the patellar mobilization which is nowadays performed manually by the physical therapist.**

This paper presents a new approach for assisting patellar mobilization during knee rehabilitation programs. The use of a robotic device for physiotherapy allows to perform exercises on a regular basis during the whole recovery period and to quantify therapy progress. The physical therapist creates a personalized training protocol depending on the patient's pathology and supervises the training program at the clinic. After several days at the clinics, the patient usually returns back home. Using the robotic device, she or he repeats predefined training sequences over several weeks. The device provides immediate feedback to the patient and the therapist. This feedback also helps the therapist to assess training progress when the patient comes to the therapy center for control sessions.

Functional tests in clinics have shown that the use of an automated device for knee therapy increases the patient's motivation and supports the physical therapist in adjusting training programs for optimal joint recovery.

Keywords: orthopaedic device, rehabilitation robotics, knee mobilization

I. INTRODUCTION

Orthopaedic surgery methods have progressed over the last years, leading to better physical performance and less invasive operations. The number of operations has increased significantly due to the aging of the population and the mobility expectation of individuals in daily activities. Surgical operation is followed by knee rehabilitation therapy, which objectives are to regain flexibility and to restore full range of motion. Scarring and knee stiffness are significant issues which can lead to loss of mobility and to impaired knee function. In particular, adhesions in the knee region lead to a decrease of knee mobility and an increase of stiffness and pain. This may even require surgery for adhesions in the joint. Kokmeyer describes the objectives of knee therapy: (1) decrease swelling and prevent further inflammation, (2) maintain and restore mobility with passive range of motion exercises; (3) maintain and restore patellar mobility, (4) and maintain quad and hamstring strength [13].

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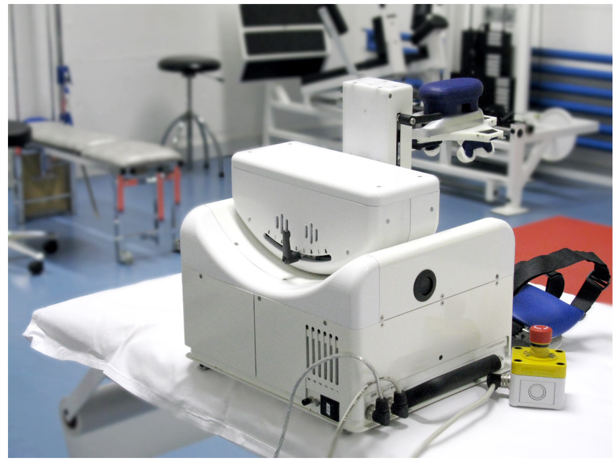

Fig. 1. Automated rehabilitation device developed at the University of Applied Sciences Rapperswil, Switzerland (patent filed). Since the device prototype is fully adjustable, the physical therapist can personalize the rehabilitation program for each patient [1].

Following surgery, orthopaedic surgeons prescribe post-operative physical therapy in most cases. This is performed either in specialized orthopedic clinics or in rehabilitation centers. Physical therapists are required to perform relatively tedious rehabilitation exercises several times a day over a few days. After returning home, patients are instructed to continue knee exercises for a few weeks, but many of them will rarely perform self-rehabilitation, due to a lack of motivation and discipline as well as a certain apprehension to do something wrong.

The paper describes here a totally new therapy approach based on a robotic device to assist knee mobilization with the aim to improve rehabilitation outcomes and accelerate recovery. The device as shown in Figure 1 can be used both in clinical and unsupervised home programs. Therapists are able to track recovery progress over an easy-to-use interface and to set relevant training parameters for clinical and home therapy. Functional tests performed in therapy centers have proven the good acceptance of such robotic device by physiotherapists.

II. RELATED WORK

A. Knee Injuries and Diseases

The knee is the largest and the most-heavily loaded joint of the human body. As illustrated in Figure 2 the knee has the function to join the femur to the tibia and is covered by some muscles, tissues and cartilages. The lateral and medial meniscus parts are located between the femur and tibia bones

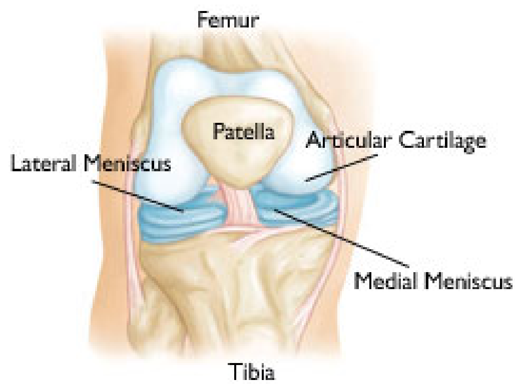

Fig. 2. Schematic representation of knee anatomy. The knee includes three bones: femur, patella und tibia [4].

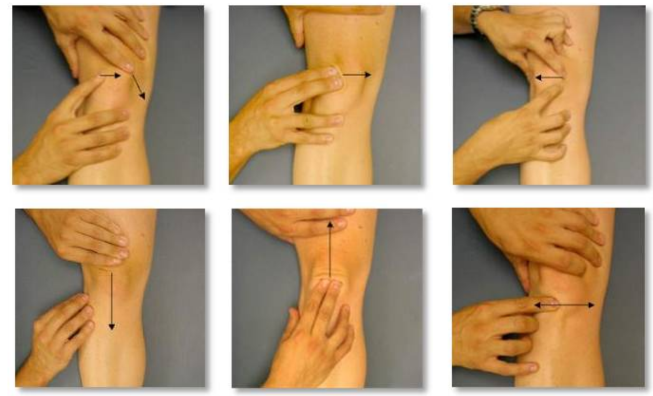

Fig. 3. Manual mobilization in medial-lateral and caudal-cranial directions. This movements shall be repeated by the physical therapist for about 10 to 15 minutes, several times a day [13].

in order to absorb shocks. The patella, also called kneecap, is the movable bone at the front of the knee and is included in a tendon that connects quadriceps muscles to the lower leg bones. Articular cartilage covers the back of the patella and provides some protection against shocks. Early mobilization of such knee region is very important in the rehabilitation process in order to prevent joint adhesion.

The knee is very often solicited during daily activities such as working, sitting, walking or running. Everyone has a non negligible probability to have her or his knee joint once affected by degenerative or traumatic diseases. With the aging of the population, a continuous increase in the number of degenerative knee diseases has been observed [11]. A common form of knee degenerative disease is osteoarthritis. Such wear in the joint cartilage is caused by a joint overuse or eventually by a previous knee injury. This disease can be very painful and reduce the quality of life. Defects in the articular cartilage may result in knee replacement surgery, also called knee arthroplasty. About 11’000 knee replacements were reported in Switzerland in 2006 and even over 500’000 total knee replacements were estimated worldwide in 2004 ([2], [8]). According to the American Academy of Orthopaedic Surgeons (AAOS) [4] in the United States, about 580’000 knee replacements are performed each year. A significant increase of knee problems is expected in the future since the population gets older and suffers from overweight problems. Additionally, traumatic lesions of the anterior and/or posterior cruciate ligaments often require surgical intervention to restore joint stability and to reduce the risk of developing knee arthritis later [11]. This type of ligament injury is fairly common by people doing sport (ski, soccer, tennis, golf) at a competition level or even on an occasional basis. A complete tear of the anterior cruciate ligament may require up to 12 months of rehabilitation. The Health Direction of Kanton Zürich (CH) estimated in 2009 overall costs in Switzerland related to anterior ligament injury to be between 200 and 250 millions swiss francs [7]. Griffin [6] estimated in 2000 the costs in the United States for the same injury to one billion US dollars. Efficient therapy methods and tools are therefore required to heal better and shorten the rehabilitation period.

B. *Knee Therapy Treatment*

In the past, post-operative treatment used to consist both in applying anti-inflammatory treatment and in immobilizing the operated joint as much as possible. Today knee physical therapy is based on progressive exercises based on motion and mobilization. These exercises pursue three main objectives. Firstly this shall increase knee extension and range of motion from the first post-operative day. Secondly this shall increase or restore the strength of muscles around the knee. Finally an important part of the therapy is to mobilize patella and soft tissues.

To regain full functionality of the knee joint, surgical intervention is followed by an intensive rehabilitation program which continues for several weeks [11]. In general, rehabilitation requires both physiotherapy sessions as well as daily home exercises by the patient. Early rehabilitation usually starts on the first day after operation and continues for approximately four weeks, which is followed by outpatient training for three months [11]. The treatment is usually performed by the therapist as long as the patient stays in hospital. After returning home, the patient is required to continue the rehabilitation program. In many cases, the therapist performs several home visits and can adjust the exercise program depending on the patient’s recovery state. The rehabilitation program aims at increasing the range of motion, diminishing pain and inflammation and preventing adhesions [12]. On the day of surgery, early motion is started with a continuous passive motion machine (CPM) [12]. CPMs are externally motorized devices which move the leg in a controlled manner with a set degree of flexion of the knee joint [9]. The first CPM devices were introduced in the eighties of the last century some time after practitioners became aware that immobilization of a joint can have detrimental effects [10].

The maintenance of patella and patellar tendon mobility is essential to regain normal range of motion and prevent the formation of adhesions in the patellofemoral joint ([5], [12]). In fact, it has been pointed out that superior mobility of the patella is crucial for complete knee function [3]. Inflamma-

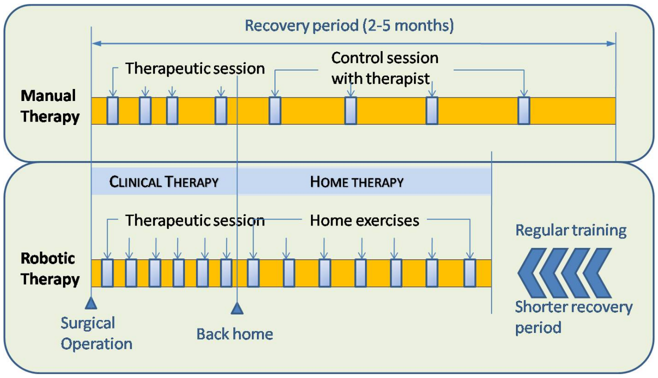

Fig. 4. Manual therapy is performed mainly during therapeutic sessions at the clinics and during control sessions. Robotic therapy can be done over the whole rehabilitation phase. Therapy is then supported by an automated device which performs therapy exercises and records progress.

tion problems often occur after surgery, which can lead to adhesions in tissues. Mobilization is applied to prevent from adhesions inside the joint spaces and scarring in the tissues around the patella. A regular patellar rehabilitation program supports the articular cartilage nutrition, prevent muscle inhibition, increase range of motion as well as increase the knee joint stability.

C. Manual Patellar Mobilization

Physical therapists recommend to perform joint mobilization immediately or a few days after operation, depending if joint swelling occurs. Common rehabilitation protocols recommend a patellar mobilization for 10 to 15 minutes for two or three times a day. The patient needs to either sit with his or her back supported by a cushion or lie on a flat surface. This body posture enables the patient to relax the muscles. The physician firstly checks swelling of the knee joint, secondly estimates pain when extending and flexing the leg and finally moves the patella in several directions. Afterward the physician starts with the patellar mobilization exercises. The amplitude of the excursion depends whether the knee is swelling and the patient feels some pain or not.

As illustrated in Figure 3, the therapist places the fingers on the knee and gently pushes the patella inward and downward (cranial to caudal). This movement must be repeated for a period of about 5 minutes. Afterward, the patella shall be moved side to side (lateral to medial) also for a period of 5 minutes. It appears less important to control the speed that to obtain in a gentle and steady motion. Patellar mobilization is performed by moving the patella manually in all four planes - superior, inferior, medial and lateral ([5], [12]). Moving the patella is not that difficult and can be incorporated into the patient's daily home exercise program [3]. However, it might eventually cause the patient some difficulties as the muscles shall be completely relaxed to achieve optimal patellar mobilization. As a result, mobilization is often performed only by a physical therapist or a partner [12]. The patient rarely performs the exercises on her or his own essentially due to a lack of motivation. In worst case, the therapy is not continued.

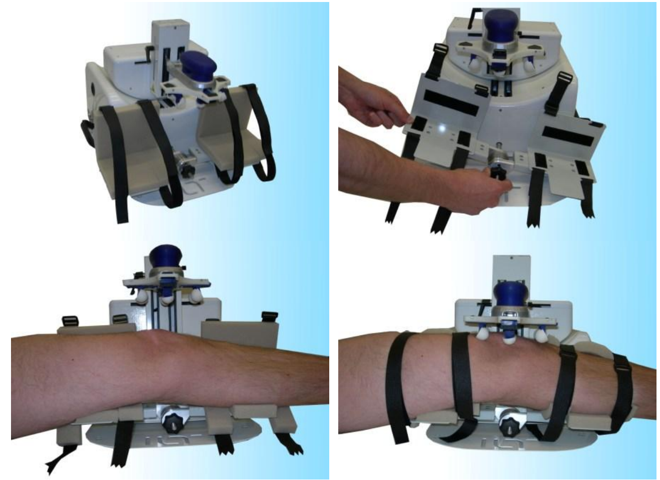

Fig. 5. The height and inclination of the leg hold-down system needs to be adjusted to the patient's size. The bending angle is also adjustable. Left top: Overview of knee rehabilitation device. Right top: Adjustment of inclination and bending angle. Left below: Leg placed onto the leg hold-down system. Right below: Patellar handling device moved down and applied to the patellar region.

III. Methods and Materials

A. Robot Assisted Therapy

The key to success in knee rehabilitation is to perform therapy exercises during the whole rehabilitation period even after the patient leaves the clinics and returns home. Compared to manual therapy, a robotic system can assist the patient in doing regular exercises over a longer period of time. Figure 4 illustrates how the robotic approach can shorten the recovery period. The patient can return back to an active job more rapidly, this having an influence on the overall health costs.

In this context, a robotic rehabilitation device has been developed which allows to automate repetitive therapy exercises and to set specific therapy patterns according to the patients pathology. This device provides doctors and physical therapists with quantitative data to monitor the patient's progress and to adapt therapeutic treatment. The patient obtains direct feedback after each training sequence.

Figure 5 shows the complete rehabilitation device developed at the University of Applied Sciences Rapperswil, Switzerland. This consists of three main parts: (1) a rehabilitation device body, (2) a leg hold-down system and (3) a patellar handling system.

B. Knee Rehabilitation Device

The main device body includes units such as linear guiding systems, motors, power amplifiers, couplings, sensors and gears. These components are arranged in a Cartesian two-axis stage which drives the patellar handling device in both medial-lateral and caudal-cranial directions. Linear potentiometers and encoders are used to provide the motor controllers with feedback signals.

The complete electronics are also integrated into the device, such that only one cable is required for communication

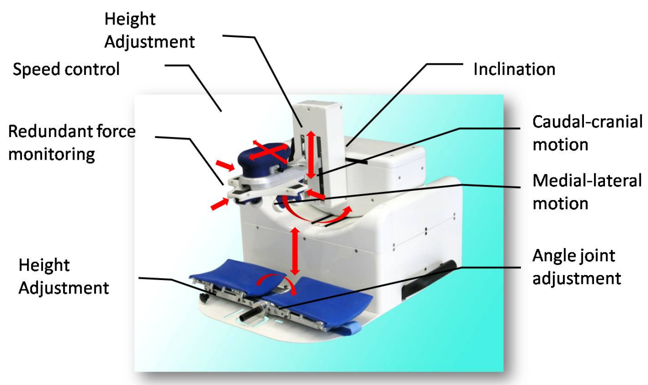

Fig. 6. The knee rehabilitation device can be fully adjusted depending on the leg's size.

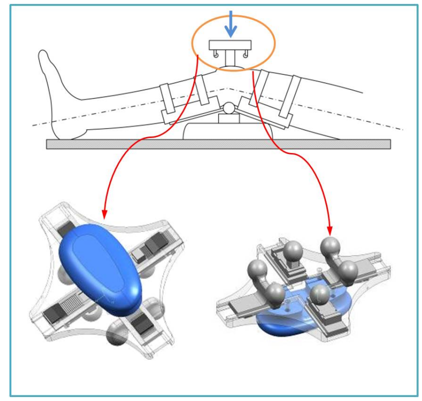

Fig. 7. Patellar handling device integrated into the rehabilitation device body. Six fingers are required to reduce contact to potential scars. Four of them are necessary for the caudal-cranial direction and two for the medial-lateral direction.

between the therapy device and the laptop. The system is powered by battery, which allows an autonomy of several training programs without the need to plug the device to a wall socket.

The adjustable leg hold-down system, as shown in Figure 5 is used to support and fix the leg using straps. The patient leg shall be either in extension or slightly flexed. The angle joint can therefore be adjusted in the range of +/-20 degrees. A leg flexion over 20 degrees may prevent patellar mobility, since the patella would be situated in the femoral groove. The leg support can be tilt in order that the patient can sit in a comfortable position. The vertical position of the leg can be also adjusted for even more comfort. A special adapter integrated in the hold-down system has been designed to stabilize the joint when being mobilized especially in the medial-lateral direction.

The patellar handling device consists of a main body and fingers with spherical ends. Those components have been produced using rapid prototyping methods. This fabrication method allowed testing complicated part geometries at reasonable costs. Finger form has been optimized to avoid pressure points and contact with scarfs. Furthermore, to further reduce pain and irritation due to contact with the handling device, silicon molds have been placed onto the fingers. The position of the fingers relative to the knee and the vertical position of the patellar handling device are fully adjustable.

C. Progress Monitoring

To ensure high patient safety, position and force sensors are integrated into the robotic device and signals are monitored continuously during mobilization. Applied forces are measured using strain gauge force sensors integrated into the adapter of the patellar handling device. Additionally, currents in the dc motors are monitored for collision avoidance and redundant force measurement. The tolerable amount of forces and displacements depends on each individual and therefore must be assessed during the teaching procedure. In the case that forces increase over the tolerable limits, the device is automatically powered down and linear axes are definitely free to move by decoupling motors from the mechanical parts using magnetic couplings. Further signals such as linear axis displacements, temperature and motor currents are monitored during therapy. If these signals are outside the expected range, the device is set automatically to the safety modus, which means that the power modules are disabled and the magnetic couplings are released. The device control has been implemented using Labview.

D. Automated Patellar Mobilization

The patellar mobilization involves two sequential phases. The first phase consists in teaching the patellar displacements, whereas the second phase is the patellar mobilization.

The learning procedure is necessary at the beginning of the therapy because both parameters, the patellar deflection and the amount of applied forces, really depend on the patient's recovery state. This procedure must be repeated only if parameters have changed between two mobilization sequences. The learning procedure can be done either manually or motorized. During the manual learning procedure, the physical therapist shifts the patellar handling device in order to push the patella to the inner and outer side as well as to the down and up side. While consulting the patient, the physician decides the maximal amounts of displacement that do not cause any pain. These values are set by pushing the specific button located directly on the patellar handling device. These displacements are then recorded to be used for the consecutive therapy as well as for the next ones.

The therapist or the patient can also choose the motorized learning modus. In this case, the robotic device gently and slowly moves the patella up and down and later left and right until the patient starts to feel some pain and signals it by releasing the activation button. The current displacements and forces are then recorded and will be used as boundary values during the patellar mobilization. The motorized learning modus is dedicated particularly to home therapy because the patient can teach the required patellar deflection while still being in a relaxed and comfortable position.

During the mobilization phase, the robotic device performs a steady displacement to mobilize the patella. Through an

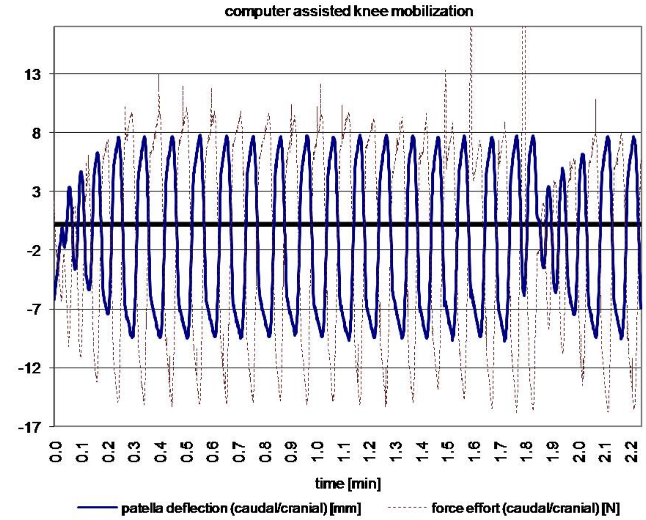

Fig. 8. Recording of forces and deflection during therapy. In this experiment, the applied force increases over a set limit after 1.8 minute therapy, the amplitude is immediately reduced and then gradually increased again.

easy-to-use Labview user interface, the therapist can set parameters such as therapy period (in minutes) and cycle rate (number of up and down movements per minute). Since the movements are fully automated, the robot assisted knee therapy is fully reproducible and traceable. By recording applied forces and displacements, not only the therapy outcome can be assessed graphically for each mobilization but also therapy results can be compared over a larger period of time. Stored data can be recalled for each patient at a later stage. This is particularly important for the knee surgeon or the therapist when the patient has done some home exercises and comes to the clinic for regular control sessions.

IV. RESULTS

A. Rehabilitation Sequence

An automated rehabilitation sequence is described here in more details. At first the deflection in the caudal and cranial directions is determined according to the learning procedure. In the motorized learning modus, the patellar handling device automatically goes in one direction very slowly until the patient starts to feel some pain and releases the activation button. The maximum amounts of excursion and force are then stored for the mobilization phase and can be uploaded several times so that the patient can repeat the therapy exercises without spending much time with setup. Afterwards, the mobilization can start. The displacement amplitude is increased gradually while ensuring a pain free treatment. The patellar is moved in the medial-lateral direction. After returning to the middle position, it is deflected in the caudal-cranial direction.

Figure 8 illustrates the forces recorded by the force sensors during therapy. The forces vary similarly to the position amplitude. The larger is the patellar deflection, the higher is the applied force. Figure 8 shows a training sequence in the

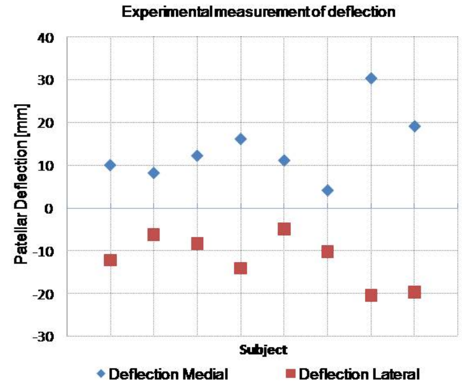

Fig. 9. The deflection in the medial lateral direction varies over a range of 4 mm to 32 mm as experimentally evaluated with 8 subjects.

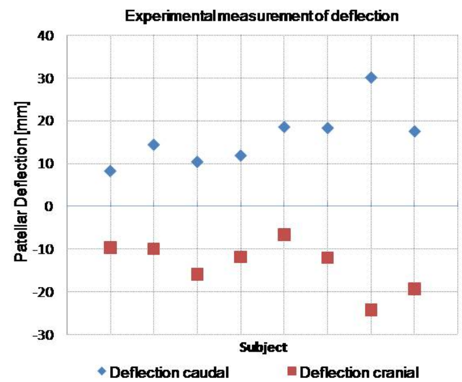

Fig. 10. The deflection in the caudal cranial direction varies over a range of 6 mm to 30 mm as experimentally evaluated with 8 subjects.

caudal-cranial direction. The force limit has been previously assessed to 20 N during the learning procedure. At first, the deflection is increased smoothly and steadily to reach a amplitude of about -/+ 8 mm. The measured forces oscillate between -15 N (caudal) and 10 N (cranial). After about 1.8 minute therapy, an external force is applied to the system to check if the force monitoring system works properly. As soon as the force overcomes the boundary limit, the deflection and therefore the forces are automatically reduced. Afterward a new training sequence starts. The force feedback ensures a pain free treatment. In case that the measured forces are outside the tolerances, the actuation system is immediately disabled and the axes are released.

B. Experimental Verification

The functionality of the knee rehabilitation device was tested in orthopaedic clinics. The automated rehabilitation sequence has been performed on eight subjects. Figures 9 and 10 show the experimental values on deflection, whereas Figures 11 and 12 report the experimental measurements of force. Large variations of deflection and force could be observed from one subject to another, which has highlighted the importance of the learning procedure in the initial phase.

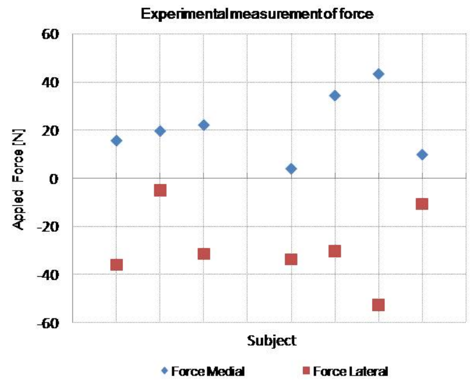

Fig. 11. The experimental evaluation with 8 subjects shows a force in the medial lateral direction between 10 to 52 N.

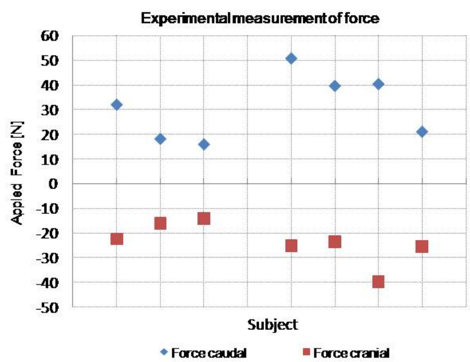

Fig. 12. The experimental evaluation with 8 subjects shows a force in the caudial craniall direction between 14 to 51 N

V. CONCLUSION AND FUTURE WORK

This paper describes an innovative approach for knee mobilization based a newly developed orthopaedic device. Using robotics in knee rehabilitation provides high benefits because rehabilitation programs can be performed in a regular and reproducible manner and the physician can concentrate on less tedious exercises. The rehabilitation device is able to self-adapt the therapy depending on the patient's needs. Through the integration of redundant measurement systems, the patient safety is guaranteed and progress can also be monitored over the whole training period. The immediate feedback improves the patients' motivation to perform home exercises regularly. An improved recovery of all knee functions can be achieved. Initial tests in orthopaedic clinics have proven the benefit of such rehabilitation technology. The next phase consists in performing clinical tests to assess efficiency with several groups of patients.

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