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# A new test rig for static and dynamic evaluation of knee motion based on a cable-driven parallel manipulator loading system

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**Abstract** The evaluation of the knee joint behavior is fundamental in many applications, such as joint modeling, prosthesis and orthosis design. A new test rig for in vitro analysis of the knee joint behavior is presented in this paper. Based on a cable-driven parallel manipulator loading system, the rig can simulate general loading conditions, such as clinical tests and common daily activities, in a wide range of flexion angles. The joint natural response in terms of movement is measured by an optoelectronic system. Furthermore, the new rig allows the estimation of the contribution of the principal leg muscles in guaranteeing the equilibrium of the joint. Despite its simplicity and low cost, the rig presents good accuracy, repeatability and versatility that allow its application on a wide range of specimen sizes. It represents an advanced application of cable-driven parallel robots for in vitro motion analysis of the knee subjected to general loads.

**Keywords** Human knee joint · Static analysis · Dynamic analysis · Test rig · Cable-driven parallel robot

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## 1 Introduction

The characterization of the kinetostatic and dynamic behavior of human joints is a fundamental step for the definition and validation of biomechanical models, that proved to be of great importance for prosthesis design, as well as for the definition of surgical treatments and rehabilitation strategies [1, 11]. Tests to measure the response of joints subjected to various loading conditions can be performed both in vivo and in vitro. In vivo tests allow the evaluation of the motion of the involved bones together with the muscle activation patterns; as a drawback, they require the use of complex and expensive techniques (MRI or fluoroscopy), or other invasive techniques (intracortical pins), or conversely less invasive skin marker techniques [9]. On the other side, in vitro tests make it possible to measure the motion of the bodies by means of trackers directly fixed to the bones. In this case, however, loading conditions have first to be measured in vivo and then carefully reproduced on specimens during in vitro tests. Similarly, muscle activation patterns cannot be measured during tests on specimens and the tissue response to load might not be the same as that of a living subject.

Several devices for in vitro tests have been proposed in the last few decades to replicate the in vivo loading conditions. Particular attention has been devoted to the analysis of the knee since this joint, together with the hip, is one of the most injured and often subjected to joint surgery. Most of these test rigs can be grouped in two main types based on their architecture, namely the Oxford Knee Rig (OKR) type [16] and the robot-based knee testing systems [12].

Both types guarantee six degrees of freedom (six DOFs) to the knee, that is to the relative motion of the femur and tibia, while external loads are applied to the joint. The general architecture of the OKR allows six DOFs to the knee by means of two kinematic chains with passive joints connecting the proximal femur and distal tibia to the frame [16]. The two chain purpose is to replicate the hip and the ankle joint motion. In particular, they permit the vertical translation of the simulated hip, to induce the leg under study to mimic the knee flexion. During this vertical motion, a vertical load is generally applied to the distal femur to reproduce the body weight. A variable force is also applied to simulate the quadriceps effect, thus realizing a controlled flexion–extension of the knee. If these characteristics are common to all the OKR type machines, the developed models differ mainly for the way the ankle and hip joints are realised and the level of generality of loads they can apply. Some refined versions of the rig, for example, allow the simulation of the leg posterior, i.e. flexor, muscles besides the quadriceps [2, 13, 14]. Other solutions guarantee the application of more general loads similar to those of daily activities [10]. These OKR-type testing machines are widespread since they are simple and leave six DOFs to the knee joint. They are particularly suitable for the evaluation of the knee kinematics under loads. However, unless their complexity increases, they are unlikely to provide general loading conditions.

On the other hand, several robot-based test systems have been developed. Usually, at every flexion angle a robot applies the load to one bone of the joint (for instance the tibia) while the other bone (for instance the femur) is kept fixed. The first robot-based knee rig was obtained by adapting an industrial serial robot [4]. In its original version, the rig was position controlled. It was used to impose certain motion paths to one bone and to measure the required forces. Then, several serial and parallel architectures were proposed. In many versions, the robot actuators are controlled in position, in order to replicate a previously measured motion or in order to obtain the desired forces at the joint [3]. In other versions, the robot operates in position control on the flexion angle and in force control on the remaining five DOFs of the bone, which moves in accordance to the applied load to reach the equilibrium pose (position and orientation) [12]. These test rigs usually require a complex hybrid closed-loop control system, which increases their costs and their overall complexity. Furthermore, most of them are adaptated from the industrial field, therefore their performances are not optimized for knee joint test applications. For instance, several robotic systems do not reach the high flexion angles necessary to test the knee joint in its whole range of motion. Although they allow the application of general loads, their complexity and their cost, together with their limited performances, represent barriers to their spread.

To overcome the principal limitations of the available test rigs, a new test rig for measuring the knee joint motion has been developed and is presented in this paper. The rig represents an evolution of a previous test rig, devoted to the execution of clinical tests [15]. Based on a specifically designed cable-driven parallel manipulator, the new rig provides general loading conditions to the joint, while preserving the characteristics of the previous version in terms of simplicity, low cost and accuracy. In particular, the rig can be used to evaluate both the loaded and unloaded behavior of the knee in a wide range of flexion, while the applied loads are changed in real time with flexion during the simulation of a given task. All motion components of the joint (except the flexion angle) are unconstrained, in order to not impose unknown reactions that would modify the results: forces are imposed, while joint rotations and displacements are free and measured, for instance by an optoelectronic system. The rig is also equipped with a system that simulates and controls the leg main muscle forces, and that allows the estimation of the muscle forces that guarantee the joint equilibrium at the considered loading conditions. By this system, indeed, muscle forces required by a given task can be experimentally obtained rather than imposed to the joint based on published data. Despite the low cost and simplicity, the new rig shows high accuracy and repeatability of measurements. The rig technical requisites and the adopted design solutions will be presented in the following session.

## 2 Description of the test rig

### 2.1 Test rig technical requisites

The purpose of the new rig is the in vitro evaluation of the behavior of the knee joint in loaded and unloaded conditions. The evaluation of the behavior in unloaded conditions consists in the measurement of the relative pose of the tibia and the femur at each knee flexion angle, when virtually no loads are applied to the joint. For the behavior in loaded conditions, the relative poses are measured when loads related to several given tasks, such as clinical tests and daily life activities, are applied to the joint. The rig, thus, is required to let the tibia move freely with respect to the femur at each imposed flexion angle according to the applied loads, i.e. when either virtually no loads or known given loads are applied. Therefore, the rig must not introduce unwanted additional constraints to the motion components.

The test rig must be able to apply general loading conditions typical of the most common tests. Indeed, the load history during flexion strongly depends on the task: when executing clinical tests (such as the anterior drawer), in fact, loads are applied along one anatomical axis (e.g., the anterior–posterior axis); on the contrary, more general loads are applied to the joint when replicating daily activities (such as walking, sit-to-stand and squat) [1, 7, 8]. Furthermore, the rig must simulate the most important muscle forces and evaluate their contribution in motion: when simulating daily activities, muscles play an important role in providing the joint equilibrium and applying significant forces.

In the design of the test rig, a wide range of motion has been considered, in order to allow tests both on healthy and on diseased knees. In particular, if a coordinate system is defined according to [6], the following ranges of rotations and translations of the knee must be guaranteed: 130° of flexion/extension, ±30° of ab/adduction and ±40° of intra/extra rotation; ±10 mm of medial/lateral, ±40 mm of anterior/posterior and 40 mm of distraction displacements [5, 11]. In all these rather wide ranges of motion, the test rig must be able to apply the loads.

The test rig must allow easiness of specimen unmounting and remounting, together with the possibility of a precise repositioning of the specimen itself within different tests. Indeed, several experimental procedures and protocols require that some tests are repeated on the same specimen but at a different time, as, for example, before and after the implantation of a prosthetic device, thus making it necessary to unmount and remount the specimen from and to the test rig. Similarly, the specimen should be precisely aligned with the rig according to some anatomical landmarks, so that the applied loads have exactly the desired directions with respect to the joint. Loading conditions should also show a good repeatability. These characteristics are important to guarantee the consistency among the measurements from several tests on the same or different specimens. Since tests are performed on specimens with a wide range of sizes, the test rig is required to be versatile and easily adjustable for any leg size. The device has to be cheap and easy-to-clean. Finally, its usage in contact with human specimens determines some limitations on the materials chosen for its construction.

### 2.2 Overall description of the rig architecture

The whole frame of the rig is formed by square section standard aluminum profiles, fixed together by means of standard angle connections and bolts. The frame is made up of two parts, as shown in Fig. 1: a base (5) and a movable portal (1). The portal is connected to the base by a revolute kinematic pair (revolute joint). Figure 1 shows a schematic of the test rig in a plane orthogonal to the above said revolute axis. Point O is the trace of the revolute joint axis. The femur (3) is connected to the portal; the tibia (10) is housed in a ring (6), then firmly fixed to it by specifically designed clamping devices. The ring represents the platform of a cable-driven parallel manipulator by which a generic wrench can be applied to the tibia. Additional details of the loading system will be given in the next subsection. Except for the flexion angle, the relative position and orientation of (6), i.e. of the tibia, with respect to the femur is determined solely by the constraints imposed by the knee anatomical structures. The base is fixed with respect to the laboratory.

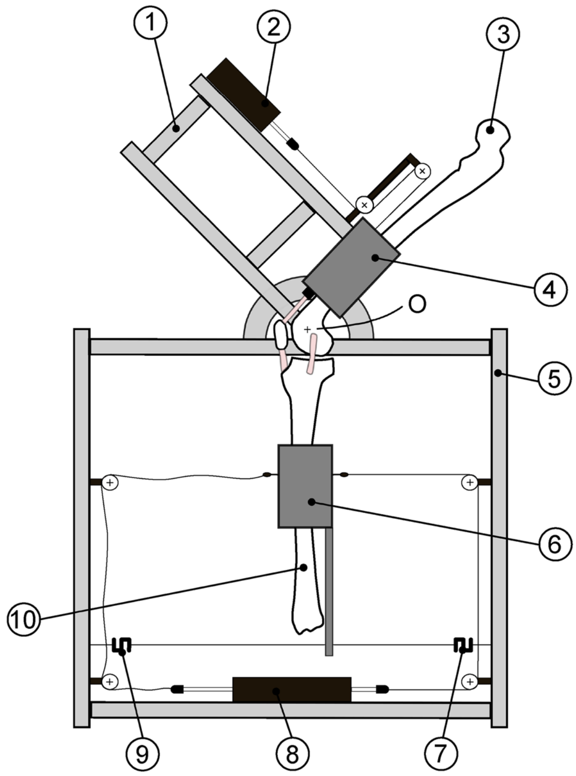


**Fig. 1** Test rig structure: portal (1); single-acting pneumatic actuator (2); femur (3); femur fixation system (4); base (5); tibial ring (6); load cells (7) and (9); double-acting pneumatic actuator (8); tibia (10)

Pneumatic cylinders for the loading system are fixed to the base. Figure 1 shows only one of these (8) for clarity. The knee flexion angle is set by rotating the portal and changing the angular position of the femur while keeping the axis of the tibia vertical, as described in the following sub-sections. A flexion angle of 135° can be reached. To minimize the relative gross motion between the tibia and the frame, the specimen is mounted on the rig in a way that the physiological flexion axis (i.e. the transepicondylar femur axis, identified by the surgeon) is coincident with the revolute joint axis between the base (5) and the portal (1). Also, in this way the flexion angle of the joint and the applied loads can be controlled more easily and with a higher precision.

The femur is mounted on the portal by a fixation system (4). The flexion angle can be controlled, by rotating the portal about the revolute joint axis. The femur fixation system is composed of an adjusting device and a reference device. The former makes it possible to adjust the pose of the specimen with six DOFs with respect to the rig during specimen mounting, by using three translations and three rotations. The pose of the femur with respect to the rig can thus be precisely controlled. Once the specimen is positioned on the rig, these six DOFs are locked, making the femur fixed to the portal. The reference device allows unmounting and precise repositioning of the femur, and it is composed by a femur fixation shell and a reference element; the former is rigidly connected to the femur by clamps and can be dismounted together with the bone, while the latter is part of the adjusting device. The shell can be univocally located with respect to the reference element so that they can be dismounted and remounted in the same relative pose, thus allowing the specimen to be accurately repositioned with respect to the rig, between two tests.

Both the tibia and femur clamps are designed to guarantee the anchoring of the bone by friction, so that no bone preparation is needed and each single bone can be utilized for further tests. All clamps are realized in stainless steel, as they enter into contact with the specimen and need to be sterilized after each test, and are covered in sandpaper.

### 2.3 Cable-driven parallel manipulator based loading system

When executing a loaded test, at each flexion angle given loads are applied to the tibia, while its motion with respect to the femur is measured by a stereophotogrammetric system. An original loading system has been devised to apply any desired system of force and moment, i.e. any desired wrench. The system is based on a cable-driven fully parallel manipulator, whose movable platform is the tibial ring (6) (Fig. 1). As shown in Fig. 2a, the tibial ring (6) is driven by a system of 12 cables two by two, $(a_1, a'_1)$, $(a_2, a'_2)$, …,$(a_6, a'_6)$, acting in the same direction. Each pair of cables $(a_i, a'_i)$, $i = 1, 2, \ldots, 6$, belongs to a closed loop (realized by means of pulleys) which includes a double-stroke pneumatic actuator (8) with double-ended piston rod as reported in Fig. 1. Each cable is slightly slack, as shown in the same figure, in a way that while the tensioned side of the loop provides a force to the tibial ring, the natural motion of the tibia is not resisted by the untensioned side. At any angular position of the portal (femur), i.e. at any knee flexion

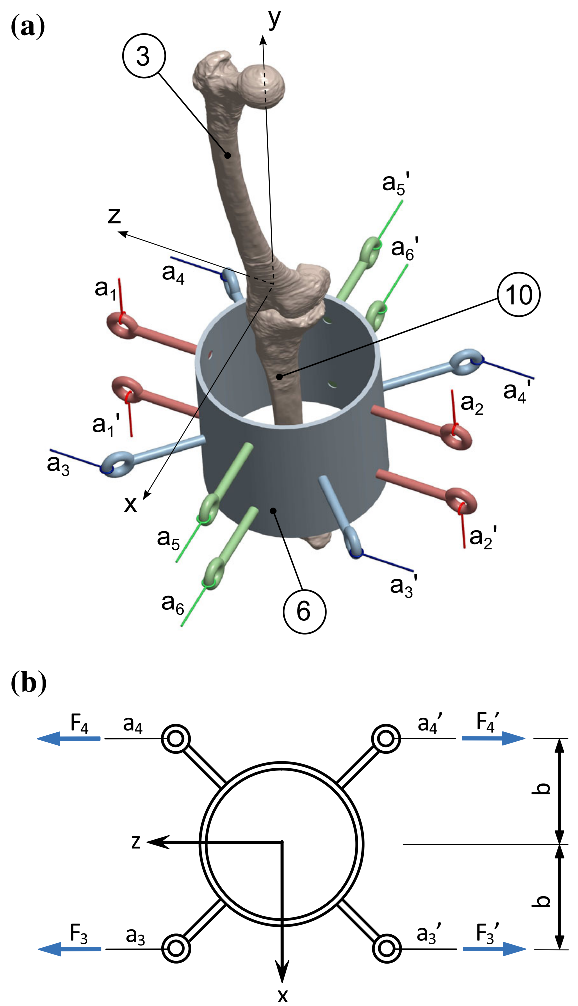


**Fig. 2** Detailed representation of the tibial ring which is the movable platform of the cable-driven parallel manipulator for the tibia loading system. The particular configuration of cables and connections guarantees the decoupling of forces and moments. Different combinations of forces in loops 3 and 4 allow the application of a pure force along z axis or a pure moment along y axis or a combination of these two. **a** Cable arrangement and connections for the tibia loading system: femur (3); tibial ring (6); tibia (10). **b** Simplified representation of a pair of cables working together

angle, only one branch of each of the six pairs will be in tension according to the wrench to be applied to the platform (tibia), the other corresponding branch being slack. In particular, the cylinders work in pairs. Each pair generates a force and a moment component respectively along and about one of the three axes of a reference system whose z-axis is parallel to the portal rotation axis, x-axis is directed anteriorly with respect to the tibia and y-axis is orthogonal to the other two, as shown in Fig. 2a.

The pneumatic actuation is an important feature that provides an inherently force control system, thus allowing the loaded tibia to freely move in space with respect to the femur. In particular, as previously noted, the femur rotation is imposed by the portal, while the tibia is free to change its pose. Five DOFs are left to the tibia with respect to the frame: the tibia is free to move in order to reach the equilibrium pose, due to the effect of the loads and of the knee structures (articular surfaces, ligaments and muscles when activated); only the projection of the tibia longitudinal axis on a plane perpendicular to the portal revolute axis is constrained to remain vertical in order to control the flexion angle. This feature is achieved by an additional force control system that will be described in Sect. 2.4.

The arrangement of the cables and their connections to the tibial ring are represented in Fig. 2a and are such that, in a relatively large workspace of the tibial ring, the wrench provided to the platform can be practically fully decoupled. For instance, loops 3 and 4 (i.e. pairs of cables $(a_3, a_3')$ and $(a_4, a_4')$) work together in order to guarantee a medio/lateral force and an internal/external moment (i.e. a force along the z axis and a moment about the y axis). With reference to Fig. 2b, a pure medio/lateral positive force $F_z$ is obtained if cables $a_3$ and $a_4$ are tensioned and apply the same force $F$:

$$F_z = F_3 + F_4 = 2F \tag{1}$$

Similarly, a pure internal/external positive moment $M_y$ is obtained if cables $a_3'$ and $a_4$ are tensioned and apply the same force $F$:

$$M_y = F_3' b + F_4 b = 2Fb \tag{2}$$

Any combination of force $F_z$ and moment $M_y$ is obtained by different combinations of forces in loops 3 and 4. The adopted configuration leads to an intrinsic optimisation of the single force applied by each actuator. Because of these features the control system is very simple and efficient.

Furthermore, the loading system allows an easy application of the load conditions typical of the clinical tests used to verify the stability of the knee: the anterior drawer, the internal/external rotation and the abduction/adduction tests can be easily performed by actuating only one cylinder pair. Maximum force components allowed by the present actuation system are 2400 N for any of the three directions x, y and z previously defined; maximum moment components are 100 Nm about z axis and 300 Nm about x and y axes. These values already consider the effect of friction in the cylinders and pulleys, that were experimentally evaluated in preliminary tests and introduced as a control parameter in the control code. These ranges of forces and moments guarantee the replication of the loads of the most common daily activities, like walking, squat and sit-to-stand tasks.

This actuation system thus allows the simulation of several loading conditions, by applying to the tibia through the tibial ring a system of forces equivalent to those measured during both clinical tests and daily activities. In the latter case, the forces exchanged between the foot and the ground can be measured in vivo by means of a force platform. A preliminary estimate of the tibia motion is also obtained in vivo by standard techniques. The equivalent system of forces at the tibial ring can be calculated by considering the approximate relative pose of the tibia with respect to the ground at each instant of the task and by a straightforward equivalence between force systems: ground forces are transformed in an equivalent system of six forces along the cables by the control code, that computes the pressure required by each cylinder. The equivalent system of external loads is defined and applied to the tibia for each flexion angle, according to the specific task. When the flexion angle is changed by rotating the portal, a transducer communicates the flexion angle to the control system, that modifies the pressures in the pneumatic actuators accordingly.

### 2.4 System for the simulation of muscle forces

While in unloaded motion and during clinical tests no muscle is involved, when executing daily activities muscles play an important role in guaranteeing the equilibrium of the knee joint. A system has been developed to take into account the muscle contribution during in vitro tests. This system simulates and controls the effect of the most important muscles responsible for the knee flexion and extension, namely the quadriceps on the anterior side, and the hamstrings and gastrocnemius on the posterior side. To guarantee a physiological positioning of the patella, a minimum load (70 N) is applied by the quadriceps during every test. The quadriceps is simulated thanks to a single-acting pneumatic actuator (2) (Fig. 1), fixed to the portal and connected to the quadriceps tendon by means of a clamping device. Its position and orientation can be adjusted in order to align the quadriceps force to its anatomical direction. Since it is mounted on the portal, the cylinder maintains the same position with respect to the femur when the flexion angle is changed. Conversely, no actuator is dedicated to the simulation of the muscles on the posterior side: they are simulated by applying an equivalent load to the tibial ring. To determine this load, at each flexion angle two force lines of action, one for the hamstring and one for the gastrocnemius, are evaluated and an estimation of the ratio between the magnitude of their forces is taken from the literature for each task, so that the line of action of the resultant of the posterior muscle forces can be obtained. The magnitude of this resultant is found by the control system and it is then applied to the tibia by superposing its effect to those of the equivalent external loads.

The control system for the muscle force simulation is based on two cables, one anterior and one posterior, that connect the tibial ring to the frame distally via an aluminium bar, as shown in Fig. 1. Two load cells (7) and (9), positioned between each cable and the frame, measure the tension in the cables in the anterior/posterior direction. The difference between the two tensions is used to control the system for the simulation of the quadriceps or the posterior muscles. The control system works in order to make the difference of tension in the two cables equal to zero, so that flexion/extension moment due to external loads is equilibrated only by the simulated quadriceps or posterior muscles and by the other knee internal structures (ligament and contact surfaces) at the given flexion angle. If, as a consequence of the external loads, the knee tends to flex as shown in Fig. 3a, the anterior cable is tensioned and the cylinder simulating the quadriceps is activated to eliminate the difference in the two cable tensions, thus maintaining the tibia in a vertical position. Conversely, if the knee tends to extend as shown in Fig. 3b, the posterior cable is tensioned and posterior muscles are activated: based on the superposition principle, additional loads, equivalent to the resultant force of the flexor muscles, are applied to the tibial ring. Thus, loads at the end of the aluminum bar are maintained generally low by the control system, except eventually during transient state. However, the bar is thick and rigid in order to

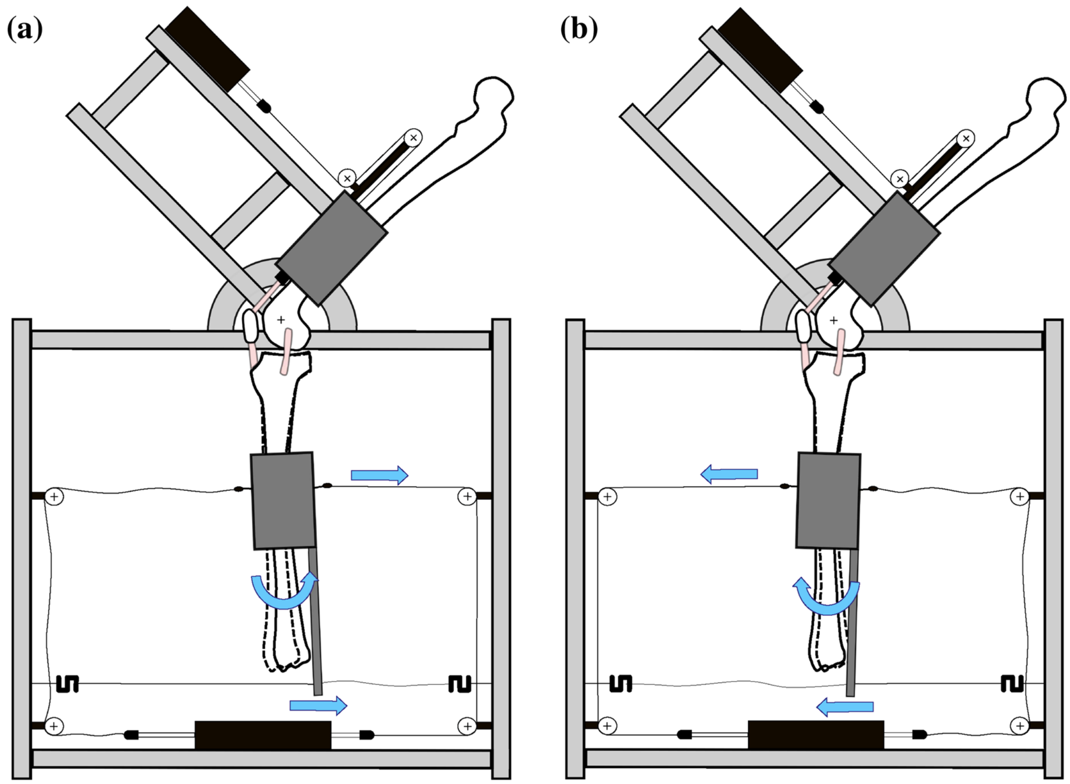


**Fig. 3** The rotation of the tibia due to the applied forces introduces a difference in the load cell signals. This difference controls the muscle simulation system. **a** If the knee flexes, i.e. distal tibia moves backward, the anterior load cell is loaded. **b** If the knee extends, i.e. the distal tibia moves forward, the posterior cell is loaded.

avoid deformation and to not influence the muscle control system.

This system makes it possible to simulate the real effect of the muscles on the tested leg. Indeed, it applies a load that balances the knee flexion/extension moment and allows the evaluation of the muscle contribution during daily activities. However, only the difference of the action of the antagonist muscles can be evaluated, since the present control system does not consider co-contraction of anterior and posterior muscles.

## 3 Experimental validation of the rig

In order to evaluate the performances of the proposed rig, a single specimen was investigated, performing both unloaded and loaded tests. A surgeon declared the leg free from anatomical defects and removed the foot and all the soft tissues, leaving the knee joint capsule intact. A stereophotogrammetric system (Vicon Motion Systems Ltd., nominal accuracy 0.5 mm/0.5°) was used to measure the relative motion among the tibia, femur and patella by means of three trackers (Figs. 4 and 5) directly fixed to the bones, thus introducing no soft tissue artifact.

The so prepared specimen was connected to the rig through the femoral fixation system on the portal (Fig. 5). The following tasks were performed: passive flexion first and then squat and sit-to-stand, by connecting the tibia to the ring (6) in Fig. 1 and applying the corresponding wrenches. The external forces employed for the loaded tasks were taken from the literature [1, 7, 8]. Loading and unloading ramps were introduced at the beginning and at the end of the motion tasks. Four flexions were performed for each task and the relative motion of the femur with respect to the tibia was expressed by means of the Grood and Suntay notation [6].

The accuracy of the rig was experimentally evaluated by comparing the different paths of the

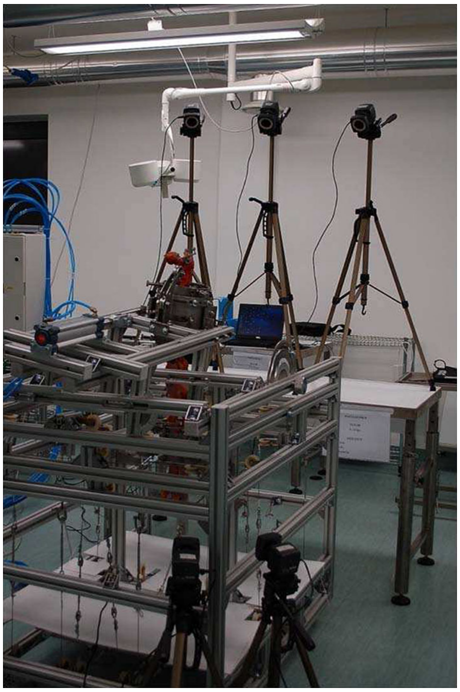

**Fig. 4** During the experimental session, the test rig hosts a specimen and is surrounded by the cameras of the sterephotogrammetric system adopted for motion analysis

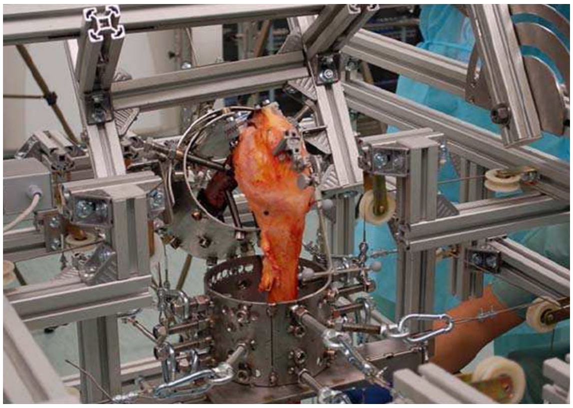

**Fig. 5** A detail of the specimen and the clamping devices

relative motion of the femur with respect to the tibia. Figure 6 shows the mean value of the intra–extra rotation of the tibia versus the flexion angle for the three considered tasks. In all cases, the resolution of the rig allows the observation of a hysteretic behavior of the joint. Table 1 shows the mean standard deviation (SD) of each of the coupled components of the femoro-tibial motion (namely intra-extra rotation, ab-adduction, antero-posterior, medio-lateral and proximo-distal translations), evaluated for each task. The small magnitude of SD provides indications about the repeatability of the proposed rig. Even when mean motions are computed without distinguishing between flexion and extension, namely when hysteresis is not considered, the resolution of the system makes it possible to distinguish between two very similar tasks such as squat and sit-to-stand (Fig. 7). Finally, Fig. 8 shows the net muscular forces generated by the rig during the squat and sit-to-stand. As expected, the contribution of the extensor muscles exceeds the flexors for both tasks. Although the external loads associated with these two tasks are similar, the muscular activation produced by the rig can distinguish between the two, correctly identifying the squat as the most demanding of the two tasks.

## 4 Discussions

The purpose of this work was to develop a new test rig, able to investigate the behavior of the human knee under loaded and virtually unloaded conditions in a wide range of motion. The developed rig presented in this paper is a simple and economic solution that satisfies this specification.

The pneumatic loading system together with the actuation system, based on a cable-driven fully parallel manipulator, makes it possible to apply desired loads while the tibia moves to an equilibrium pose. This allows the evaluation of the natural behavior of the tested joint, since the application of the load does not imply any additional constraints to the knee motion other than those imposed by the anatomical structures of the knee joint.

The specific geometry of the loading system allows a decoupling between the force and moment components applied to the tibia, thus simplifying the force control. Actually, a full decoupling is present only at the neutral pose. During tests, the movement of the tibia (10), and consequently of the tibial ring (6), with respect to the frame modifies the directions of the cables, and consequently the lines of action of the applied forces, thus causing the coupling of forces and moments. Nevertheless, the control system acts as if forces and moments were fully decoupled during the test. This simplification is acceptable, since the distances between each cable insertion point on the

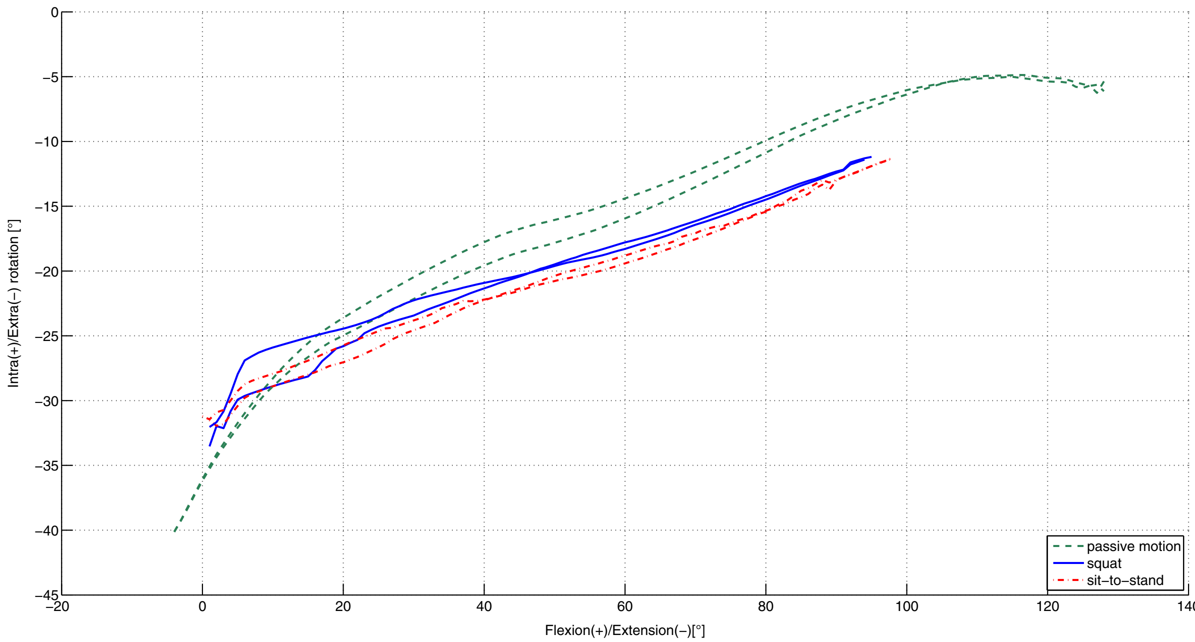


**Fig. 6** Intra/extra rotation of the tibia during passive flexion, sit-to-stand and squat. Hysteretic behaviour can be observed

**Table 1** Standard deviation values (SD) of the five motion parameters for passive motion, squat and sit-to-stand tasks

| | Ab/Ad (°) | Int/Ext (°) | Ant/Post (mm) | Prox/Dist (mm) | Med/Lat (mm) |
|---|---|---|---|---|---|
| Passive motion | 0.05 | 0.09 | 0.19 | 0.13 | 0.15 |
| Squat | 0.13 | 0.41 | 0.42 | 0.15 | 0.22 |
| Sit-to-stand | 0.24 | 0.38 | 2.76 | 0.41 | 2.05 |

tibial ring (6) and its respective fix point on the frame (corresponding to the pulley) is large if compared with the motion components, so only small changes in the directions of the forces are produced. In addition to this advantage, the use of the cables for the platform actuation offers the possibility of fixing the pneumatic actuators directly on the base of the frame, thus reducing the rig size and decreasing the moving inertias.

The choice of a pneumatic actuation allows a simple open chain control, since pneumatic actuators are inherently controlled in force through their pressure control. Force-feedback signals are not necessary, though they can be added in order to improve the accuracy of the load control. Tests have been executed to characterise the influence of friction on each complete loop and results of the measurement have been considered in the control code, as explained in Sect. 2.3. Despite this calibration, some uncertainties on the applied loads still remain on the rig, mainly due to the effects of the static friction at the beginning and at the inversion of the motion at the actuators. Alteration of the applied forces and the stick-slip effect can arise in these circumstances, and they cannot be considered by the control code. The choice of a different kind of actuation (for example, electrical) could help in eliminating this source of uncertainty on the applied wrench. It is worth remembering that wrenches applied during tests are mean values taken from experiments reported in the literature, not directly measured on the tested specimen. So the above mentioned uncertainties are small if compared with this approximation and they can be accepted.

Unlike other devices that impose muscle loads, at each flexion angle the control system allows the evaluation of the net moment provided at the knee by

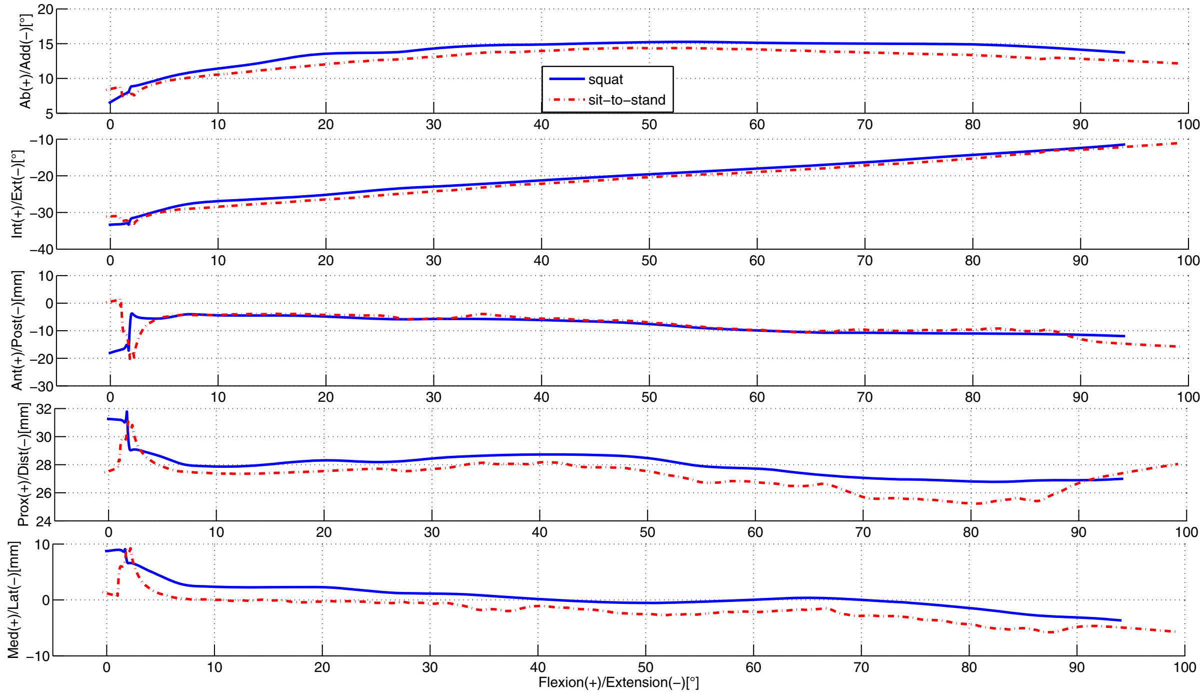


**Fig. 7** Motion parameters of the relative motion in squat and sit-to-stand tasks

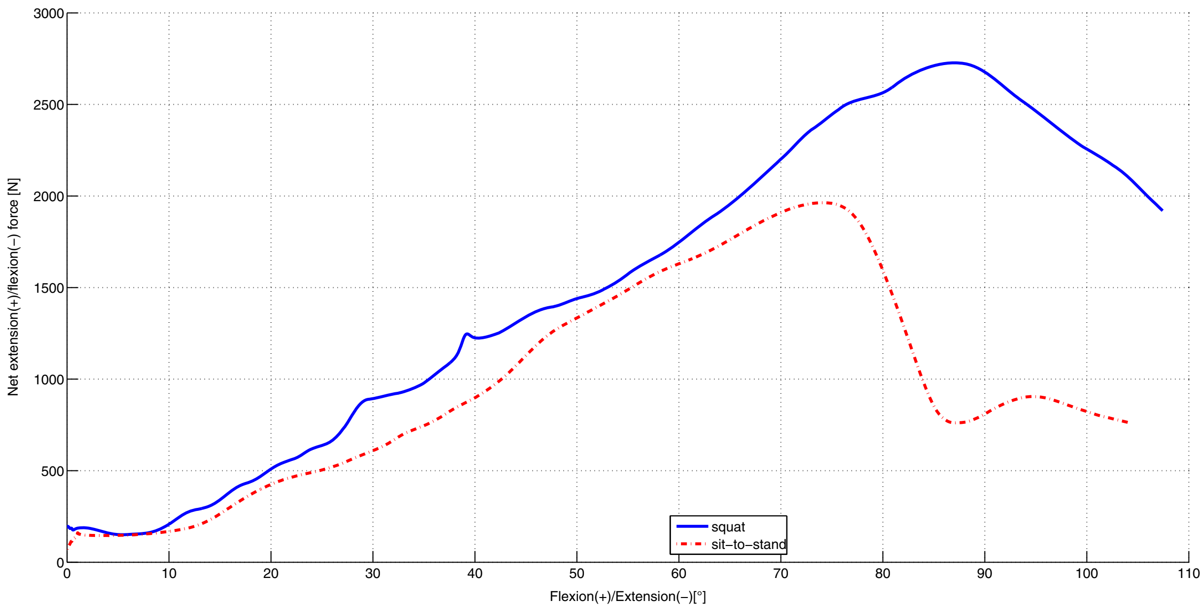


**Fig. 8** Net force during execution of squat and sit-to-stand tasks

the leg muscles in guaranteeing the equilibrium to rotation around the O axis. The net joint moment is the result of the difference between the moment generated by anterior muscles and the moment generated by posterior ones, since contemporary contraction of anterior and posterior muscles is often present during motion. While the difference can be evaluated by the machine, the contribution of each single muscle cannot be identified, since infinite combination of forces would guarantee the equilibrium to the considered rotation. If some muscular forces or a proportion between anterior and posterior forces were imposed, co-contraction could be taken into account. In this case, further hypotheses would be introduced, thus bringing in some not well known variables. The authors chose not to introduce other variables and to consider that either anterior or posterior muscles are activated, as shown in Fig. 8.

The test rig proves to be versatile: all possible loading conditions within a certain range can be applied and can be modified as a function of the flexion angle, thus simulating different loading tasks. In addition, the dimension of the clamping devices do not impose particular constraints on the specimen size. With some simple modifications also other joints, for instance the ankle and the elbow, can be tested. The concept behind the rig design makes its construction very simple and economic in comparison with other devices available in the literature. Indeed, the rig was designed and assembled in the laboratory and the costs for materials and components were less than 7000 euros. The rig is also easy to set up and clean.

Despite its simplicity and low cost, the rig together with the measuring system showed good accuracy and repeatability during the executed preliminary tests. Figure 6 and Table 1 show the good repeatability of the motion obtained in loaded and unloaded tests; Figs. 7 and 8 show the good accuracy in terms of both measured motion and estimated net joint force, that allows the distinction between two very similar but different tasks: sit-to-stand and squat. A more in-depth analysis of the rig behaviour will be performed but the preliminary results are encouraging. The design of the clamping and the adjustable device offers a good accuracy in positioning and repositioning the specimen, that was unmounted between tests.

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