Simulator of the Spatial Location of the Knee Axis of Rotation During Flexion

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***Abstract*— Knee simulator mechanisms use a single degree of freedom and do not consider Genu varum and Genu valgum clinical scenarios in design, leading to a lack of a comprehensive approach to treating knee pathologies. This research aims to provide healthcare professionals and researchers with a knee simulator that allows them to understand knee biomechanics in depth, considering a wide range of clinical scenarios. The results of the angular kinematics analysis concluded that the simulator can reach up to 140° and emulate a Genu valgum of 7.6° of deviation and a Genu varum of 8.9° of deviation.**

Keywords: Knee simulator, Polycentric Knee, Mechanism, Genu varum, Genu valgum.

I. INTRODUCTION

The knee is one of the most essential and complex joints in human locomotion [1]. It is vulnerable to sports injuries and pathologies that can cause chronic pain, limit mobility, and lead to disability [2]. It is necessary to develop knee simulators to study biomechanical behavior, deepen the knowledge of injuries and diseases, and generate possible treatments [3].

There are several types of knee simulators, but their systems simplify biomechanical movement by considering the knee as a hinge, so they have limited mobility and do not consider the translation of the rotation axis. Currently, the polycentric mechanism is widely used because it approximates the biomechanics of the knee. Still, the orthotic industry does not consider ”Genu varum” and ”Genu valgum” deviations in its design [4]. These are deviations in the legs; specifically, valgus is prone to injury due to misalignment of the patella [5]. So far, no new mechanisms have been applied to knee simulators to add an extra degree of freedom, and a comprehensive approach to treating knee pathologies is needed. This is why there is a need to provide researchers and healthcare professionals with versatile tools to understand knee biomechanics, help them generate better treatment options, and even validate knee kinematic ranges for other devices or test them before commercialization.

This research aims to provide a way to achieve natural translation and rotation in knee biomechanics and to allow healthcare professionals and researchers to analyze a broader range of clinical scenarios by considering ”Genu valgum” and ”Genu varum” deviations for the development of flexion motion. For the purposes mentioned above, a knee rotation axis simulator is introduced. It starts with the requirements to develop it, continues with the conceptual design and CAD design, and ends with the angular kinematics results.

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II. DESIGN OF THE POLYCENTRIC KNEE MECHANISM

A VDI2221 methodology is used to design the knee simulator, which starts with the system requirements, a conceptual design, and necessary components [6].

A. Requirements

The basic requirements for developing the knee simulator were established using the state of the art of knee prosthesis manufacturing and the various mechanisms for lower limb prostheses as a basis.

- Main function: The system should emulate the knee flexion. Finally, the aim is to obtain 2 degrees of freedom to approximate the movement to the real knee biomechanics. In addition, the knee simulator should emulate genu valgum and genu varum conditions.
- Geometry: Anthropometric measurements shall be used for a person of 1,75m height. The knee height shall be approximately 49,9cm [7].
- Type of mechanism: The mechanism shall be designed to allow rotation and translation movements. In this way, the 2 degrees of freedom will be achieved in the knee simulator.
- Maximum flexion angle: The leg shall be attached to a test stand and reach 140°.
- Device weight: The knee simulator shall be designed to weigh approximately the same as devices already available on the market: 2 to 3.5kg.
- Material for manufacturing: PLA filament and 3D printing will be used to manufacture the knee simulator.
- Target audience: This article does not consider using the prosthesis on a person. The main objective is to emulate the movement of the knee considering two degrees of freedom and the ”Genu varum” and ”Genu valgum” morphologies.

III. CONCEPTUAL DESIGN

To explain the design of the mechanism, it is necessary to define the context in which the prototype will work

Fig. 1. Deviations: (a) Genu varum, (b) Genu valgum [13].

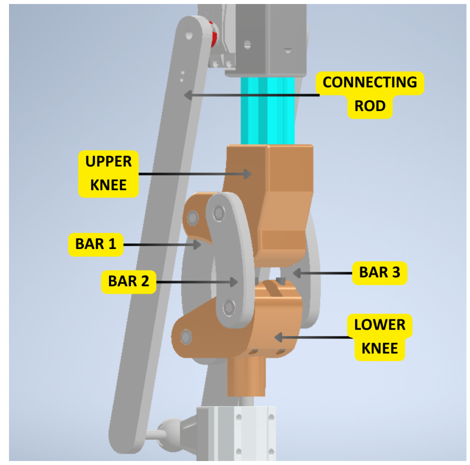

Fig. 2. Knee simulator.

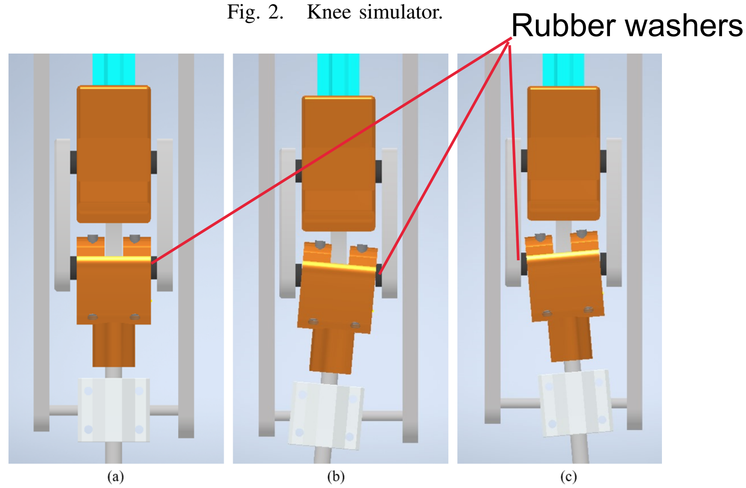

Fig. 3. Simulation of deviations: (a) Normal (b) Genu Valgum (c) Genu Varum.

because this is a knee simulator oriented to validate devices similar to a goniometer, variables such as stress analysis of the mechanical components, stability during flexion or control adjustment, will not be substantial for the operation of the mechanism. However, since the aim is to emulate the behavior of a natural knee, it will be necessary to add parts that allow more degrees of freedom to establish Genu Varum and Genu Valgum conditions, in addition to the rotation and translation of a knee and an angle of 140° of flexion [8]. For these reasons, the design implementation is based on a polycentric knee, which can be adapted to meet the requirements of the prototype.

The polycentric knee arises from biomechanical adaptation; this type of knee varies the center of rotation, depending on the position in which it is located, and is configured using a four-bar mechanism. For this reason, it is used in prostheses [9].

The four-bar mechanism is an articulated system that uses four interconnected rigid elements to simulate the motion of the knee joint [10]. The proposed mechanism can perform flexion and extension in a single plane, so an adaptation was proposed to simulate the conditions presented in Fig. 1.

The Genu Varum condition, also known as ”bowlegged”, is a condition in which the knees are spread apart while the ankles are closer together, giving the appearance of an outward bow in the legs, as shown in Fig. 1 [11].

The Genu Valgum condition is characterized by ”X-legs”, in which the knees are closer together. At the same time, the ankles are separated, giving the appearance of an inward bow in the legs, shown in Fig. 1 [12].

A. Proposed four-bar mechanism

The proposed design takes elements similar to commercial prostheses, thus configuring a four-bar mechanism [14]. The main mechanism is composed of an upper knee, a lower knee, and 3 bars, which are coupled by an axle, and washers are adjusted using rubber, as shown in Fig. 2. In addition, the mechanism incorporates couplings (in the upper and lower knee) for a profile beam and an axis so that elements that resemble the anatomy of a lower extremity can be assembled. As well as support to assemble the DS3218 servo motor that will be responsible for providing the movement [15].

B. Adaptation to simulate Genu Varum and Genu Valgum conditions

Due to the desire to emulate the different deviations of a lower limb (Genu varum and Genu Valgum of different magnitudes), it was decided to use rubber washers that are attached to the bars that join the lower knee and the upper knee so that these can be configured for different angles, being able to rotate clockwise and counterclockwise, as presented in Fig 3. In this way, the mechanism meets the requirements to be considered valgus since it exceeds 5° of deviation, considered a mild valgus [16].

C. Movement of the mechanism

During the flexion movement of the knee, the associated movement must be rotational [17]. For this reason, we chose to use a servomotor (DS3218), which has sufficient torque to rotate the lower part of the mechanism. The rotational movement of the servomotor is transmitted using 2 rods coupled to the lower axis using a linear bearing. This configuration allows a range of 140° in the flexion.

D. Analysis of equations

Taking a plane containing the profile mechanism, the simplified mechanism diagram for kinematic analysis is presented in Fig. 4. The system comprises a four-bar and a crank-crank mechanism arrangement. The four rods provide the multicentric knee simulation, and the crank-crank provides motion to the system [18].

The first closed loop (1) is composed of the vector $\vec{a_6}$ and vector $\vec{a_4}$ starting from point O_6 to point E then to point C. Then the vectors $\vec{a_1}$ and vector $\vec{a_5}$ starting from the same point O_6 and arriving at the same point E close the loop.

The second closed loop (2) is composed of the vector $\vec{b_1}$ and the vector $\vec{a_2}$ starting from point O_6 to point O_2 and then to point A. Then the vectors $\vec{a_6}$, $\vec{b_4}$, $\vec{s_4}$ and $\vec{a_3}$ starting from the same point O_6 and arriving at the same point A, close the loop.

The vector equations are decomposed into scalar equations to determine the angular relationship between the links, which are (3), (4), (5) and (6). The trigonometric relationships are completed respecting the constant angles of 70 and 90 degrees at EDB and DBA points, respectively.

Loop analysis

$$\vec{a_6} + \vec{a_4} = \vec{a_1} + \vec{a_5} \tag{1}$$

$$\vec{a_6} + \vec{b_4} + \vec{s_4} + \vec{a_3} = \vec{b_1} + \vec{a_2} \tag{2}$$

Resulting equations in the chosen plane

$$a_6 \cos(\theta_6) + a_4 \cos(\theta_4) = a_1 \cos(\theta_1) + a_5 \cos(\theta_5) \tag{3}$$

$$a_6 \sin(\theta_6) + a_4 \sin(\theta_4) = a_1 \sin(\theta_1) + a_5 \sin(\theta_5) \tag{4}$$

$$\begin{aligned} a_6 \cos(\theta_6) + b_4 \cos(\theta_4) + s_4 \cos\left(\theta_4 - \frac{11}{18}\pi\right) + \\ a_3 \cos\left(\theta_4 - \frac{10}{9}\pi\right) = b_1 \cos(\theta_{b_1}) + a_2 \cos(\theta_2) \end{aligned} \tag{5}$$

$$\begin{aligned} a_6 \sin(\theta_6) + b_4 \sin(\theta_4) + s_4 \sin\left(\theta_4 - \frac{11}{18}\pi\right) + \\ a_3 \sin\left(\theta_4 - \frac{10}{9}\pi\right) = b_1 \sin(\theta_{b_1}) + a_2 \sin(\theta_2) \end{aligned} \tag{6}$$

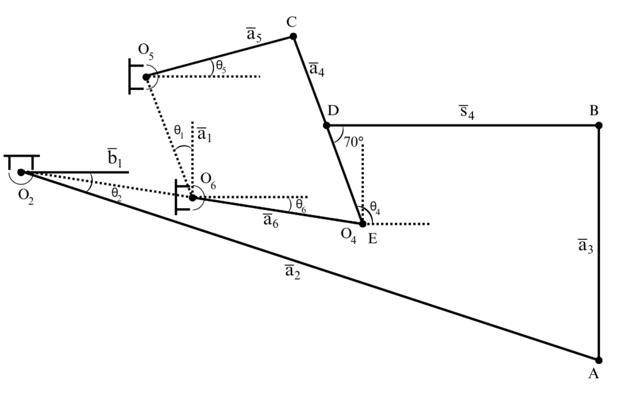

Fig. 4. Skeleton of two-loop mechanism: Vector loop.

E. Main components

To execute the assembly, various commercial elements were used to address the fundamental parts that make up the structure: the calf, the thigh, and the mechanism that emulates a knee. Among them are rubber rings with an approximate diameter of 4.76 mm. Allen head screws, grade 12.9, with diameters of 5 mm and various lengths adapted to the specifications of our design, covering measures of 10mm, 30mm, 35mm, 40mm, 60mm, and 100 mm in length. We have also incorporated carbon steel grade 8.8 captive head bolts with 3mm and 5mm diameters in this assembly process. Other elements used in the process include two roller bearings, a linear bearing with an internal diameter of 8mm, a tube 8mm in diameter and 1mm thick, aluminum nuts with a diameter of 5mm, a ridge cap used to cover the hollow end of the tube and a male ball joint with a rod. The electronics for the knee simulator used an Arduino, a breadboard, jumper wires, a voltage regulator, and a 20kg DS3218 servo motor.

IV. TESTS CARRIED OUT

Two tests were carried out, one with a digital goniometer and the other with videogrammetry.

A. Movement ranges with a digital goniometer

Once the assembly was completed, a first test was conducted with a GemRed 82305 digital goniometer with a resolution of 0.1°.

B. Capturing video data for analysis in Kinovea

Once the system had been assembled on the test bench and the 20kg servomotor, Arduino, and voltage regulator had been connected, we proceeded to capture video data to be analyzed in the Kinovea program. A Sony "FDR-AX700" model camera was used.

C. Range of Motion Results with a Digital Goniometer

The digital goniometer indicated an angle of 41° between the component simulating the thigh and the component simulating the calf. The first test indicated an angle of 139° for flexion.

D. Results of video data capture for analysis at Kinovea

Programming on the Arduino allowed us to bring the component that simulates the calf to the following angles at different times: 30°, 60°, 90°, 120° and 140°. Fig. 5 shows the 60° and 120° positions.

Fig. 6 presents the graph demonstrating that the knee simulator has a flexion angle greater than 140° degrees when viewed from the sagittal plane and with the hip in flexion. It is important to note that flexion can reach up to 140° when the hip is flexed and up to 120° when the hip is extended.

In addition, the angle of the "Genu varum" and "Genu valgum" conditions was validated. Fig 7 (a) corresponds to a morphology without deviation. Fig 7 (b) is a valgum with 7.6° of deviation, and Fig 7 (c) is a varum with 8.9° deviation.

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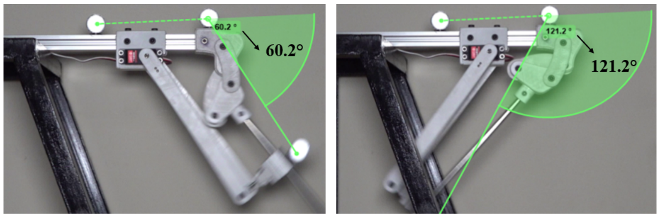


(a) (b)

Fig. 5. Data analysis in Kinovea, (a) to 60°, (b) to 120°.

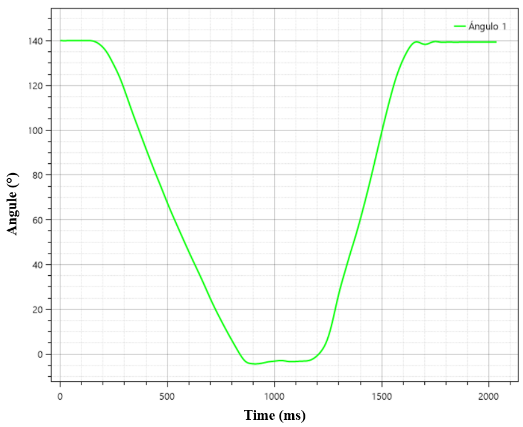
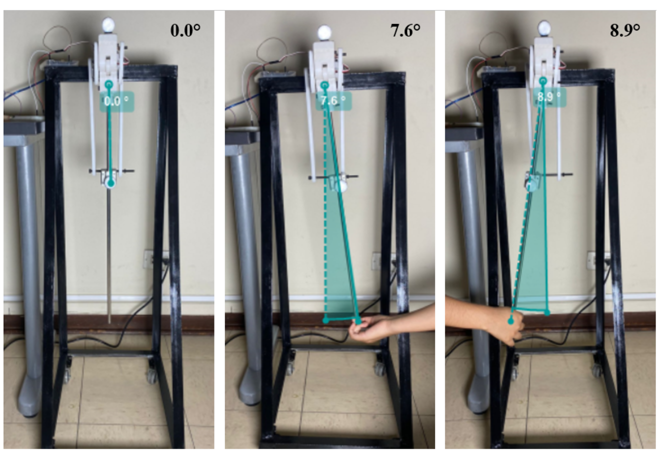


Fig. 6. Angle vs. time graph.



(a) (b) (c)

Fig. 7. Validation of deviations.

V. CONCLUSIONS

The knee simulator helps to improve the understanding of knee biomechanics and will facilitate the validation of other devices, such as goniometers or orthopedic medicine devices, for general patient care. The mechanism is readily manufacturable and can be replicated by other researchers for application in their research.

The knee simulator meets the requirement of up to 140° of flexion. It can also emulate Genu varum and Genu valgum conditions depending on the position to which it is set.

Knee simulators and similar mechanisms contribute to the progress of science as they can be adapted to the anatomical particularities of amputee patients to be studied.

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