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Modular child lower limb phantom with seven degrees of freedom simulating micrometric bone growth

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Abstract

Children's growth is a fundamental parameter in paediatrics for assessing physical development. The growth measurement at short time intervals, of typically four weeks, is based on the length of a long bone, mostly the tibia. All measurement methods are contact methods, and they are unsuitable for uncooperative children or younger than 3.5 years old and are significantly affected by soft tissue deflection (STA). A solution could be to use non-contact optical methods. The main challenges in applying such solutions and achieve growth measurement uncertainties below 0.5 mm, are STA, establishing models between the target measurement and the bone growth, and measurement system errors. To enable the validation of various solutions, initially without the influence of STA, a modular phantom of a child's lower limb is proposed that simulates growth in the range 0-12.7 mm for the femur and tibia. The phantom enables movements imitating the motion of the lower limbs, for the hip joint in three degrees of freedom, and in two degrees of freedom for the knee and ankle joints in ranges based on literature data. A ball joint and two universal joints are used. In their current form, all joints have a fixed center of rotation which will allow to test the assumption that growth can be studied using optical systems. Thanks to the modular design of the phantom, in the future, the original knee joint could be replaced with a polycentric mechanism based on a four-bar mechanism with an additional rotational joint, which will correspond to the kinematics of the knee joint. The growth is produced using three manual actuators, and measured with an integrated micrometer located on the central axis tubes, aligned with the joints, to avoid Abbe errors.

Lower limb phantom; growth measurement; anatomical joint simulation;

1. Introduction

The measurement of children's growth is a basic parameter used in pediatrics to assess a child's physical development. To verify the impact of illnesses, medication or diet on a child's development and respond promptly to any undesirable changes the measurement must be done at short time intervals [1] based on the long bone measurement, specifically, the tibia, which growths less than 0.5 mm per day for infants [2] and ~0.4 to 0.5 mm per week for older children [3].

Among the known methods of measuring growth, the most popular is the knemometric method [2–4]. Results obtained using this method are subject to significant errors due to the deflection of soft tissues (STA). Another method [5] is the contact method, also referred to as non-contact measurement conditions, which involves the simultaneous measurement of force and length. However, this method does not allow newborns and toddlers to be measured. The solution to this problem may be the use of optical methods. The main challenges in applying such solutions are STA, determining the centers of rotation of joints (CoR), and measurement system errors [6].

For the lower limb growth values, the determination of the CoR of the joint should be to an uncertainty of the order of one tenth or 0.05 mm for daily growth or 0.35 mm for weekly growth. For this reason, it is essential to develop a phantom that mimics the hip, knee, and ankle joints and simulates bone growth but is independent of STA in order to evaluate the performance of the growth measurement method.

The lower limb contains three joints of varying complexity in terms of anatomical structure and kinematic relationships. The movement of the lower limb is described in three main planes: Sagittal, Frontal/Coronal, and Transverse [7] (Figure 1).

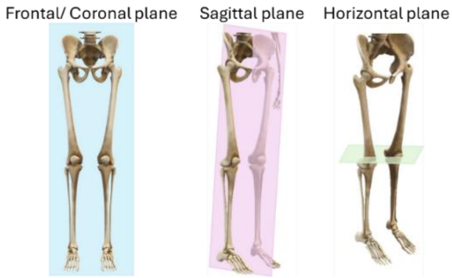

Figure 1. Anatomical planes

The average values, along with their corresponding axes, are presented in Table 1. The values are based on literature [8–11].

Table 1. Anatomical ranges of motion (RoM) of the joints (S – Sagittal, F/C - Frontal/Coronal, T – Transverse)

Joint	Movement	Plane	RoM [°]
Hip	Extension/ Flexion	S	-30/125
	Abduction/ Adduction	F/C	-50/30
	Internal/External Rotation	T	-45/45
Knee	Extension/Flexion	S	-15/135
	Abduction/ Adduction	F/C	-15/15
	Internal/External Rotation	T	-40/30
Ankle	Extension /Flexion	S	-45/20
	Pronation/Supination	F/C	-30/20

The hip joint allows for combined rotation in all three planes of motion. The knee joint is one of the most complex joints in the human body. It has one dominant axis of movement in the sagittal plane (-15° /135°) and two with a more limited range in the transverse (-40° /30°) and frontal/coronal (-15° /15°) planes [11]. The abduction and rotation must occur only when the joint is bent in the sagittal plane. Due to the anatomy of the knee joint, it provides six degrees of freedom. Thus, during flexion, there is a conjugation of translational and rotational motion, which in turn results in the displacement of the center of rotation of the knee as the joint flexes [12]. Additionally, knee joint movement varies depending on whether it is loaded or unloaded [13]. This is due to the ligaments in the joint, which can change the presumed movement of the joint when significant dynamic forces are applied (e.g., during running or squatting). The ankle joint has two axes of rotation in the sagittal and frontal/coronal planes [14].

The phantoms described in the literature depend heavily on the characteristic being tested. One of the phantom groups focuses on tissue properties and limb appearance, but does not consider joint structure and movement. These phantoms are used in electromyography [15], where they simulate muscles and their chemical and electrical properties, or in radiology [16], where bone marrow, compact bone, and soft tissue are reproduced to study the effects of irradiation. The second group of phantoms focuses on movement reproduction, which also includes prosthetic and orthotic elements. In orthotics, exoskeletons are one of the most advanced lower limb reproductions [17]. Focusing on movement assistance, they are required to reproduce movement well, but usually with a limited number of degrees of freedom compared to human anatomy. In the case of functional lower limb prostheses [18], the primary goal is to replicate movement by replacing anatomical joints with mechanical joints, without focusing on replicating appearance. For the knee joint, a hinge or polycentric joint is most commonly used. In this group, in addition to replicating kinematics, the key factors are the dynamic properties and durability of the construction. There is a gap, then, with the phantom that simulates bone growth, which could be used to validate methods of bone growth measurement without STA.

2. Materials and methods

The methodology describes the process of constructing and validating the phantom, including the assumptions and simplifications made in comparison with the anatomy of the lower limb.

2.1. Construction of the phantom

The most important requirement for a lower limb phantom is the capability to simulate and measure bone growth while maintaining the best possible representation of real lower limb kinematics. Additionally, the phantom should be designed to limit the impact of thermal phenomena and ensure the modularity of the entire mechanism, allowing for future modification and expansion.

Bone growth is the most critical assumption and requirement for the phantom to function. Therefore, the phantom is designed to ensure measurement accuracy of no less than 0.05 mm, and a growth of 12.7 mm for the elements of the tibia and femur, which corresponds to the growth of a newborn, toddler, and older children in the time interval of up to 4 weeks.

The extension element is based on two center-axis round tubes (base tube and carbon tube). The length is adjusted using a microadjuster located outside the tubes, connected by rods. The movement is triggered and locked by turning the nuts on the rods, which allows for precise adjustment and locking of the desired length. The nuts are marked on one side to ensure that each one has the same rotation. The change of length is measured with a micrometer nominally located on the axis between the two consecutive joints (hip-knee and knee–ankle) to avoid Abbe errors. A schematic representation of the growth element is shown in Figure 2.

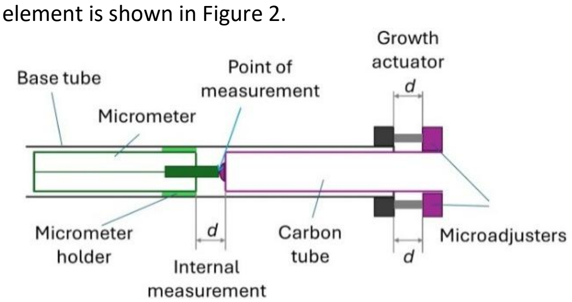

Figure 2. Schema of the growth mechanism

Two extension elements simulating growth areas were used in the phantom at the parts corresponding to the femur and tibia. Due to the slow growth of the foot, which is not proportional to overall growth, and the lack of influence of foot growth on the displacement of other joints, it was designed as a fixed-length element in the phantom. To ensure thermal stability, the parts simulating bones are made of carbon fiber. A schematic representation of a connection of growing parts with joints forming a phantom is shown in the figure below (Figure 3).

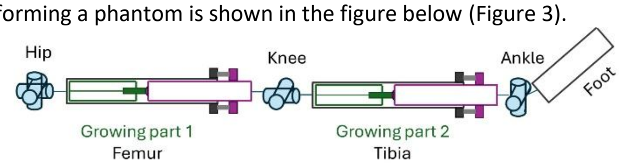

Figure 3. Kinematic schema of the phantom

Anatomical joints have a complex structure that is not fully reflected by familiar mechanical joints. However, since the main element of the phantom is the growth of the link between joints, standard mechanical elements were selected to best approach anatomical movement.

The hip joint is a spherical joint. It therefore allows for combined rotation in all three planes of motion: Sagittal, Frontal/Coronal, and Transverse. To replicate this behavior, a ball joint was selected as the mechanical representation.

The primary movements of the knee and foot that must be considered in the phantom are flexion and extension. Additionally, both joints allow for movement in the frontal/ coronal planes. On this basis, a universal joint was selected as the best mechanical representation. It simplifies the movement of the knee by neglecting the movement in the transverse plane and assuming a fixed center of rotation.

SolidWorks 2025 was used in the design process. Where possible, standard components were used, and the remaining components were manufactured using the Mazak Quick Turn Nexus 200 CNC Turning Center.

2.2. Validation of the phantom

The validation was conducted in two stages. The first stage involved verifying the representation of anatomical angular ranges of motion for the joints based on data from Table 1. The measurement was performed using the Beall Tool Tilt Box, a digital inclinometer with an accuracy of 0.1 degrees and a resolution of 0.05 degrees.

The second part of the validation concerns the increments obtained, their stability, and the accuracy of measurement using the built-in micrometer. The aim is to determine how connections, imperfections in joint construction, and mechanical slack, which may not influence the measurement with the mounted micrometer, affect the elongation of the phantom part. The tests were performed on each part of the phantom. A caliper with an uncertainty of 15 micrometers (calibrated on gauge blocks) was used to measure the lengths. The measurement of the “growing part” was taken at six length values. The next value is obtained by changing the length using the adjuster. The measurements were taken in three conditions: no external force, tensile force, and compressive force (Figure 4). The force is applied by the operator to simulate the possible displacements that could occur during the phantom movement.

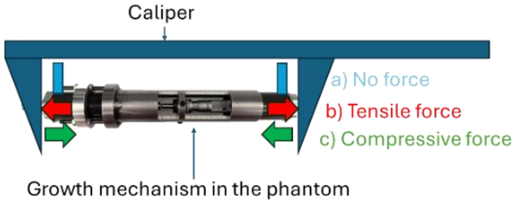

Figure 4. Validation of the growth mechanism under different conditions

Verification of the influence of imperfections in each joint, universal (Figure 5A) and spherical (Figure 5B), on construction was performed. The measurements were taken in three conditions as before.

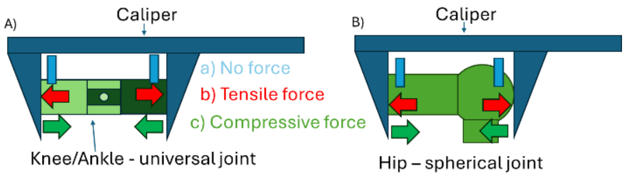

Figure 5. A) Validation of the universal joint under different conditions; B)Validation of the spherical joint under different conditions

3. Results

3.1. Phantom construction

A CAD model of the growing mechanism and the entire phantom were developed.

To simulate growth, a mechanism based on two central axis round tubes was designed as shown in Figure 7. Aligning with machining capabilities, the base element was made of low-carbon steel. Centrally mounted in this element is a Mitutoyo 148-502 micrometer with a ±0.0051 millimeter uncertainty, and the base element itself was cut out on both sides to allow access to the micrometer knob and to read the measured value. The moving "bone" element was made of carbon fiber to reduce thermal influence. A spherical measuring surface was attached to one of its ends, in contact with the micrometer spindle, to ensure the point measurement.

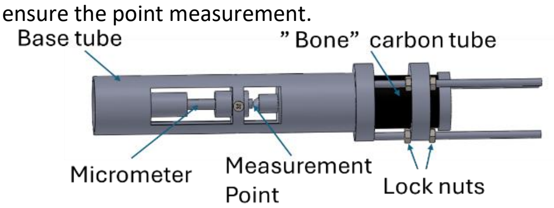

Figure 7. Growth mechanism in the phantom

Two rings, one on each tube, are permanently fixed to the tube and connected with M4 × 0.7 mm rods that act as guide rails. The length is adjusted by moving one of the tubes with the ring attached, and it is locked in position with six nuts. Height measurement using a micrometer is performed manually after a change in height.

The final model, with selected joints, is presented in Figure 8.

The entire structure is based on screw connections to ensure modularity. The connection was blocked using the threadlocker to prevent undesirable unscrewing of the model during movement. The completed and assembled phantom is shown in Figure 9.

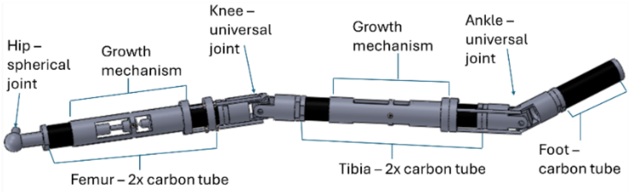

Figure 8. CAD model of the phantom of the lower limb

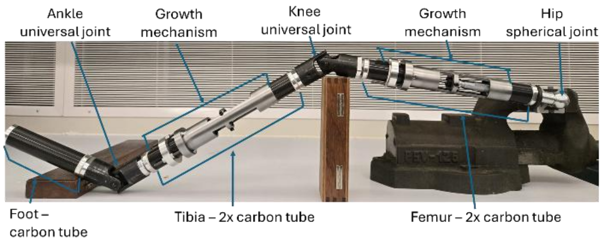

Figure 9. Phantom of the lower limb

3.2. Phantom angular movement validation

Table 2 shows the angular ranges of the Phantom joints.

Table 2. Phantom ranges of motion (RoM) of the joints (S – Sagittal, F/C - Frontal/Coronal, T – Transverse)

Joint	Movement	Plane	RoM [°]
Hip	Extension/ Flexion	S	-180/180
	Abduction/ Addaction	F/C	-28,7/28,6
	Internal/External Rotation	T	-33,21/32,53
Knee	Extension/Flexion	S	-90/90
	Abduction/ Addaction	F/C	-20,25/20,2
Ankle	Extension /Flexion	S	-90/90
	Pronation/Supination	F/C	-25,51/25,48

The use of standard spherical and universal joints means that, unlike the anatomical limb, the angular ranges are symmetrical and the values differ from the anatomical values. For the hip joint, the spherical joint in the sagittal plane has a 150-degree greater range of extension and a 55-degree greater range of flexion. In the other planes, the ball joint has a smaller range by 31.3 degrees for abduction and 12-13 degrees for internal and external rotation. In the case of universal joints, for extension and flexion, they have a range of -90 to 90 degrees, thus allowing for less flexion movement in the knee and greater motion in other directions. For a phantom in a fully extended position, the universal joint in the second rotation also allows rotation in the range of -90 to 90 degrees. However, in other positions, the range of motion is limited by the joint's design, which depends on the pose. For a condition similar to the anatomical occurrence of this movement, i.e., for a knee flexion angle of 83.25 degrees and a foot extension of -28.45 degrees, it ranges from -20.25 to 20.2 degrees for the knee and -25.51 to 25.48 degrees for the ankle.

In the case of movements with a range greater than the anatomical range, operator control is necessary when using the phantom, or it is possible to use specially designed joint limiters that will prevent non-anatomical movements. In the case of abduction and rotation in the hip and flexion in the knee, the use of ready-made joints results in the model losing approximately 30% of its range of motion in these areas. Despite this, the phantom allows for the reproduction of a significant part of the mobility and kinematics of the joints. Anatomical joint movement is not typical in standard mechanical joints. To ensure completely anatomical movement of the phantom joints, it would be necessary to design and manufacture custom joints that replicate the natural movement of the human joints.

3.3. Phantom elements validation

The results obtained from measuring the phantom's growth are presented in the chart below (Figure 10).

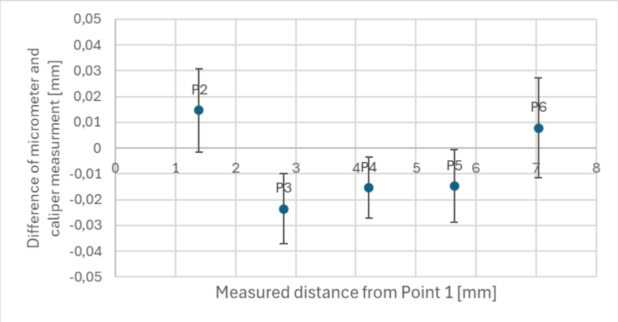

Figure 10. The difference between micrometer and caliper measurements depends on the distance (growth)

The observed differences are within the measurement accuracy of the caliper (±15 µm). No correlation was observed between the differences in measurements taken with the caliper and micrometer, regardless of the distance measured. This allows us to assume that the observed differences do not depend on the measured value, and therefore, the entire mechanism remains rigid over the entire measurement range.

For each of the six lengths, measurements were taken under unloaded conditions with tensile or compressive forces applied. An analysis of variance (ANOVA) was performed to determine whether there are statistically significant differences between the means under these conditions. For all groups, the Shapiro-Wilk test was used to verify that the data are normally distributed, and Levene's test was used to verify that the variances in the individual groups are similar. ANOVA revealed no statistically significant differences between the mean values for the length measurements performed in accordance with Figure 3 for the unloaded, compression, and tension conditions at each point (p-values = 0.85, 0.57, 0.53, 0.41, 0.85, 0.27). This means that there is no play in the growing part, so the growth of this part can be fully measured with the micrometer.

In order to validate the joints, measurements were taken under unloaded conditions and with tensile and compressive forces applied, as shown in Figure 4 and Figure 5. For all groups, the Shapiro-Wilk test showed that the data do not follow a normal distribution, so the Kruskal-Wallis test was performed to check whether the median values in the groups are equal. For the ball joint, the test showed that there is no statistically significant difference among the medians at the 95.0% confidence level (p-value = 0.679). In comparison, for the universal joint at the 95.0% confidence level, there is a statistically significant difference among the medians (p-value < 0.05). This means that during the movement of the phantom, the ball joint maintains its position, while the movement of the universal joint will depend on the force applied during the movement. The average difference between the measurements in the universal joint with compressive force and tensile force applied is 0.213 mm. The force applied was similar to that occurring when using the phantom.

4. 4. Conclusion

The phantom simulates the growth of two long bones of the lower limb. The growing part was validated, and there is no play; the uncertainty of the measurement is ±5,1 µm. However, the universal joint used to replicate the knee and ankle joints has a play of 0.213 mm. That means that the overall error of the phantom is bigger than the required 0.05 mm. The selected joints allow most anatomical movements to be preserved. However, for the universal joint used to replicate the knee and ankle joints, the differences in anatomical ranges of motion are greater than for the hip joint. As a result, the phantom is functional in its current form; however, to maintain anatomical limitations, the presence and control of the operator are necessary.

5. Future work

The phantom could be improved. In particular, a cap could be designed for the universal joint corresponding to the ankle to limit joint movement in accordance with anatomical movement. In the case of the knee, a joint could be created covering policentric center of rotation and full anatomical ranges.

5. Acknowledgment

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