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Comparative Analysis of the Motion and Kinematics of the Knee Joint Using Simulation Techniques

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***Abstract*—The World Health Organization reports 30 million people worldwide who need prosthetics and orthotics. Reports by the Consejo Nacional para la Igualdad de Discapacidades de Ecuador (CONADIS) also inform that there are 221,913 people with disabilities. This high demand has been difficult to satisfy, mainly due to the high cost of these devices. Local availability is often limited to a short/small set of size and weight configurations, forcing the patient to settle for a non-optimal option. This paper analyses the kinematics of the knee joint, based on both human gait patterns according to standard ISO 14243-1:2009, ASTM F3141:2017, and experimental results computed by our research group, which has been obtained via 3D videogrammetry techniques integrated with two force platforms. The kinematics obtained from OSSUR2000 and Streifeneder 3A20 knee joint mechanisms have been compared. For this study, SolidWorks motion kinematics and motion simulation have been used with 3D scanning technology to obtain the geometry of these mechanisms. Once analyzed and compared, a knee joint mechanism's basic design presents the flexibility to adapt to different configurations as its main feature. Finite element analysis (FEA) is important to determine the safety factor before testing it on patients. The boundary conditions are considered the parameters of the target population. According to each case, the design is considered a more adjusted safety factor and then the manufacturing step.**

***Keywords*— Motion; kinematic; knee joint; simulation; disability.**

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I. INTRODUCTION

Around the world, there are many people with physical disabilities, especially in Latin American countries like Ecuador. Most countries with limited economic resources are affected [1], [2]. There is high demand for upper and lower limb prostheses, generating the need to design and build these devices at affordable prices for our population. If we consider the import, it would be expensive. The main problem with these devices is that they are one size fits all. It is intended that the mechanism adapts to people according to their anthropometric measurements, looking in this way for the parameterization of the minimum number of dimensional values of the resulting mechanism [3].

To achieve the objective, the results of the kinematic analyzes of the ISO 14243-1 and ASTM F3141 standards are compared, standing out the main movements and forces such as flexion-extension, anterior-posterior translation (AP), Inner outer-rotation (IE), Anterior-posterior (AP) load and Axial load of the knee joint during the human walking cycle [4], [5]. The analyzes carried out in the gait laboratory of the University of Malaga are considered, taking kinetic and kinematic curves such as flexion, extension, forces, and moments, using the 3D photometry technique [6].

These graphs are compared, analyzed, and applied in two commercial knee joints like Ossur 2000 [7] y Streifeneder 3A20 [8], scanned and simulated with SolidWorks SolidWorks Motion using the finite element method. The target population's characteristics are determined through statistical, sample, and anthropometric studies. Based on these data obtained, the characteristics of the population are determined to have a base range to carry the parameterization of the knee joint [7].

II. Materials and Methods

A. Standard ISO 14243-1 and ASTM F3141 on the Use of Knee Prostheses

ISO 14243-1 is more common and established in the industry than ASTM F3141. This was first published in 2015 and then revised in 2017. The FDA (Food and Drug Administration) and multinational research organizations recommend using ISO 14243-1 [8]. ASTM F3141 is based on studies, while ISO 14243-1 is based on decades of data. The differences between ISO 14243-1 and ASTM F3141 are still unclear regarding knee replacement use. When comparing the current revision of ISO 14243-1: 2009 with the previous revision of 2002, the definition of the input curves remains the same.

The curves considered were obtained by an in vitro test to record the movements of the knee joint, using a trial template that aligns to the knee simulation setup, together with a motion capture system to obtain the medial and lateral movements of a knee replacement. Defined points on the knee are used to record kinematics from the medial and lateral flexion centers (FFC), given by the centers of posterior circular surfaces of the femoral condyles [8].

The ASTM and ISO standards that produce knee kinematics present two control modes for testing wear during simulated gait: anterior-posterior (AP) and internal-external (IE) displacement control and inputs for load control. Four inputs to the knee simulator required by ISO and ASTM are flexion-extension, axial load, internal-external torque (IE), and anterior-posterior load (AP). The flexion, axial load, and torque (IE) are similar between the two standards, but the definition of AP load is different. The variations in these inputs versus the gait cycle are presented below [8].

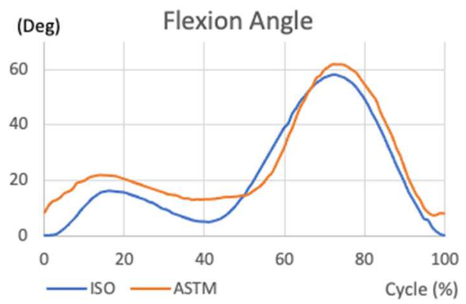

Fig. 1 Knee joint extension flexion according to ISO142431 and ASTM F3141-17

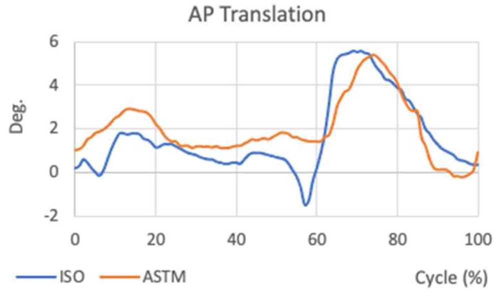

Fig. 2 Anterior Posterior Displacement in accordance with ISO142431 and ASTM F3141-17

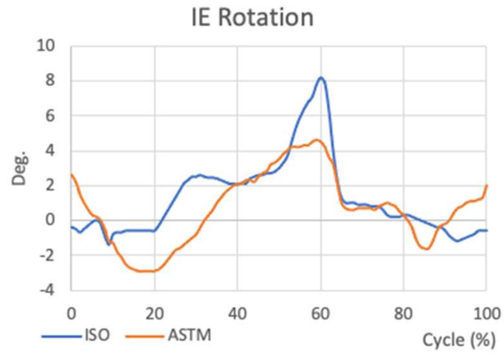

Fig. 3 Internal - external angle according to ISO142431 and ASTM F3141-17

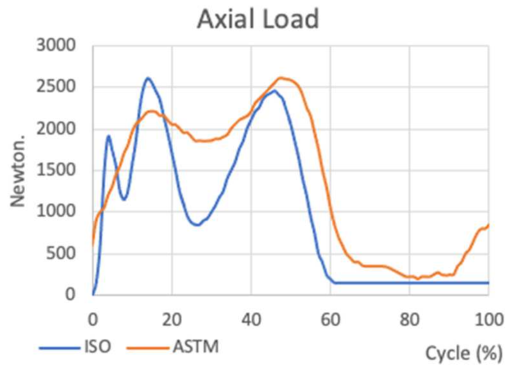

Fig. 4 Anterior-posterior load control according to ISO142431 and ASTM F3141-17

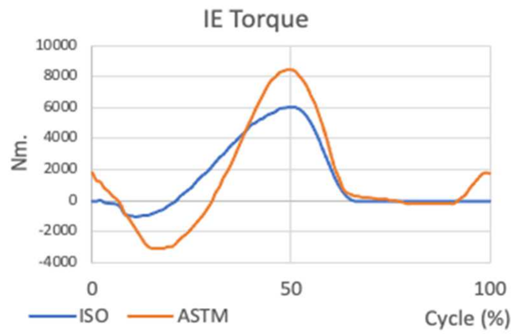

Fig. 5 Internal - external torque according to ISO142431 and ASTM F3141-17

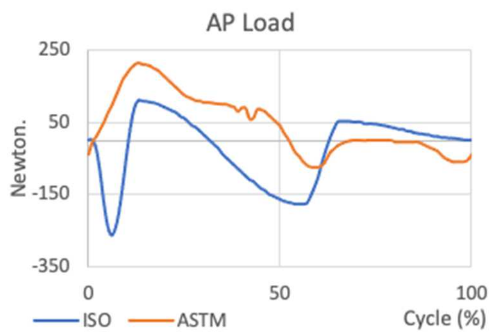

Fig. 6 Anterior-posterior loading under ISO142431 and ASTM F3141-1

B. Gait Analysis in the Laboratory

3D photometry techniques are the most used today. These are based on the recording of the movement made by a study subject on which a series of markers are placed at the points of interest [5]. By capturing these markers from different points of view, and the trajectories of the markers, through the application of a biomechanical model, it will be possible to generate the reference systems that define the body segments. Regarding the kinematics of the movement, in addition to the kinematic data collected by the motion capture equipment, it will be necessary to record the force exerted by the study subject during the tread, for which the force platforms are used.

The kinematics is obtained from the body segments by calculating the reaction forces produced in the human gait cycle to solve the problem of inverse kinetics that will result in the kinetics of movement at the joint level. To analyze the kinematics and kinetics of movements, a recording equipment will be necessary to collect data on the reaction force in the footprint. A series of auxiliary equipment such as markers, calibration sheets, and equipment for taking measurements will also be necessary as anthropometric measures [9].

C. Materials

The collection of kinematic data of the movements captured in the elaboration of this study consists of four MX-T10 cameras with Vicon Motion Systems LTD lighting and infrared reception technology, capturing at a frequency of 100 Hz. To capture the reflection of infrared light, each camera has a Vicon Vegas-I sensor, CMOS type, with a resolution of 1120x896 pixels, as shown in figure 7.

Fig. 7 MX-T10 camera, Malaga March Laboratory

The control parameters provided to each camera through the Vicon Nexus software identify the markers, calculating the centroids of each of the reflections considered valid in 2D. Thus, the data sent to the computer are the positions of the centroids in the sensor of each camera and the three-dimensional reconstruction. The MXT-10 cameras comply with the CE directives corresponding to electrical equipment for medical use according to the Declaration of Conformity attached to the documentation of said equipment.

The reaction forces of the person with the ground during support were recorded using two Kistler model 9286 A piezoelectric type dynamometric platforms with external amplification (Kistler Instruments Ins, Amherst, NY, USA), capturing at a frequency of 1000 Hz. Each force platform is made up of a rectangular rigid element made of aluminum DIN 3.3535, supported in its four corners on piezoelectric load cells that measure forces in the three directions of the space. From the forces measured by each sensor, it is possible to determine the force and moment of reaction and the location of the center of pressure.

Fig. 8 Force platform.

The force platforms' control parameters and their initialization are performed using the Kistler BioWare 3.22 software (Kistler Instruments Inc., Amherst, NY, USA). For the implementation of the biomechanical model, the Vicon Plug-In Gait 1.9 application is used, which from the trajectories captured from the markers and the data collected from the force platforms allows identifying the absolute and relative position between the links that make it up, well as forces, moments and powers at the level of the knee for the movements studied.

Given the high number of results, the normalization of the graphs and their subsequent statistical treatment will be carried out. The final graphs that give rise to the biomechanical characterization sought will be obtained with them. Markers, KADs, calibration templates are used; the markers used are passive infrared-reflective type. The KAD (Knee Alignment Device) is a device to define the axis of knee flexion in the biomechanical model.

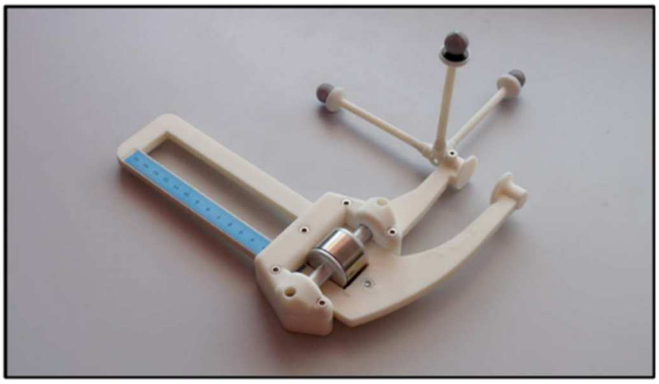

Fig. 9 Device for defining the flexion axis (KAD, Knee Alignment Device) [10].

The calibration rod is made up of two rigidly joined aluminum arms in a T-shape and on which five markers are located in fixed positions. This device is necessary for the calibration of the cameras. The most representative kinematics and kinematics curves are shown in Figures 10-12.

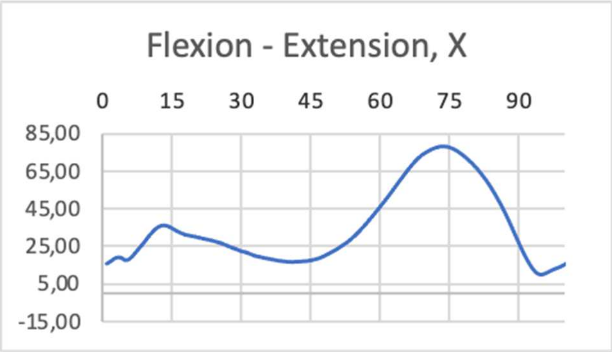

Fig. 10 Flexion extension in ¨x¨

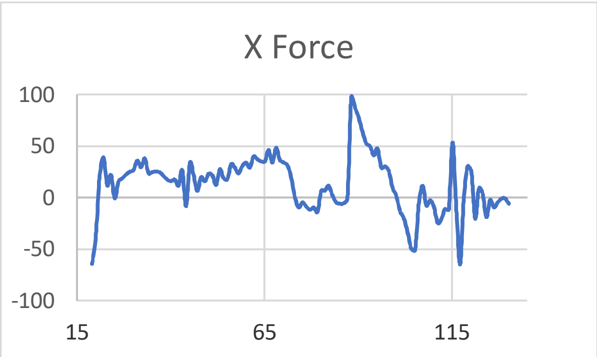

Fig. 11 Force in ¨x¨

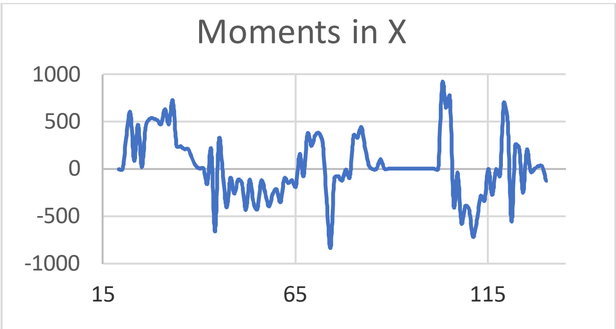

Fig. 12 Moments in ¨x¨

III. Results and Discussion

A. Knee Joint Prosthesis

FEA is a useful tool for evaluating the strength of a device before it is manufactured. Forces are simulated to obtain information on the probability of design failure when used with stresses. It is used in cases where destructive testing is impractical or when creating unique devices. This information can be used as evidence when conducting a risk assessment [11]. The International Society for Prosthetics and Orthotics (ISPO) mentions 3D printing in 2019, stating that 3D printing can be used within a range of prosthetic and orthotic applications (P&O) with the respective investigations [11].

Considering the data obtained from the kinematics and kinetics according to the ISO 14243-1 and ASTM F3141 standards in terms of prosthesis use, it is applied in two knee joint mechanisms, Ossur 2000 and Streifeneder 3A20, and comparing the results between these two mechanisms. For the development of the Ossur 2000 knee joint. It was carried out with the help of a 3D scanner from the 3D model and the SolidWorks Motion computational tool to develop its parts, assembly, and respective dynamic simulations. The curves of Figure 1 and the load were selected according to the ISO 142431 standard.

All the numerical data represented in the curves were passed to SolidWorks Motions to create the simulation environments, for this it was divided into intervals of 10% of the gait cycle, considering two aspects; the gait cycle and the maximum value of the load, obtaining a resulting table with the values of the safety factor as shown in table 1 and table 2.

Fig. 13 Knee joint Ossur 2000 [12].

For border conditions, three aspects were considered; the loads versus the gait cycle that are placed at the top of the knee joint exactly where the pyramidal coupling is by applying the forces towards the Z-axis, taking into account that depending on the cycle of the march it will have a certain angle. As fixed restrictions, the lower part of the mechanism and the internal contour where it makes contact with the pylon and the joints between elements have global type restrictions without penetration were considered. The Streifeneder knee joint simulations meet the same boundary conditions. The only difference is the geometry of the joint.

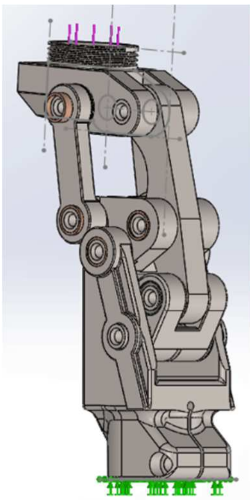

Fig. 14 Ossur 2000 knee joint digitization.

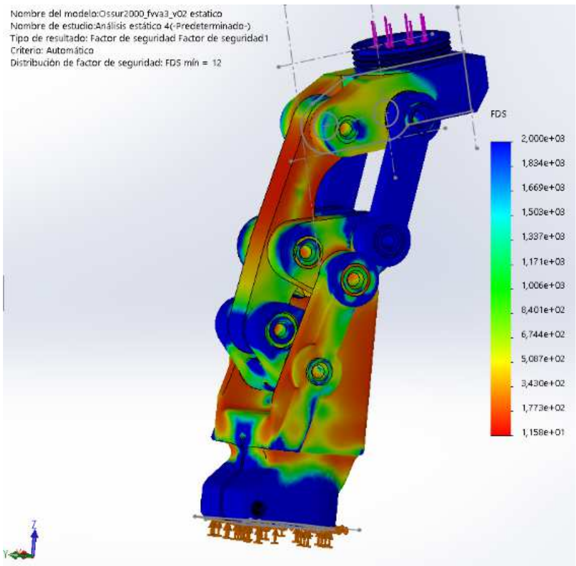

Fig. 15 Finite element simulation of the Ossur 2000 knee joint.

Fig. 16 Streifeneder 3A20 knee joint [13]

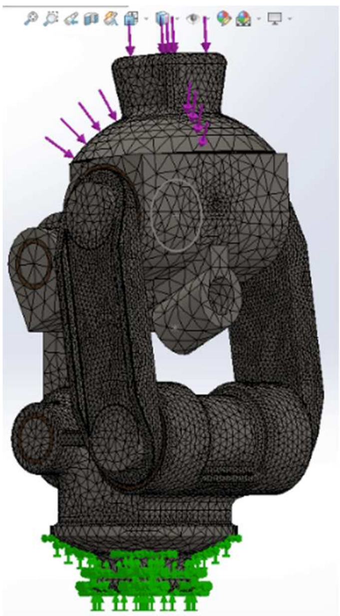

Fig. 17 Streifeneder 3A20 knee joint digitization

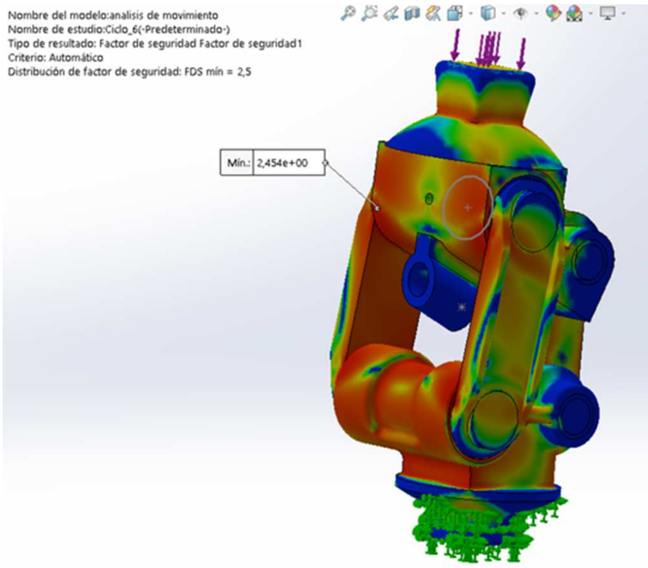

Fig. 18 Finite element simulation of the Streifeneder 3A20 knee joint

As shown in Table I, the result of the simulations of the Ossur 2000 knee joint is presented with the maximum body mass according to the manufacturer of 100 kg, obtaining the maximum loads in intervals from 10% to 100% of the human gait cycle, as the main result the safety factors are determined, presenting a minimum value of 5.2 in 56% of the gait cycle with a load of 178 N and whose mesh is 170602 elements.

TABLE I
GAIT ANALYSIS, OSSUR 2000

Gait analysis points, Ossur 2000				
CYCLE	**ISO Deg**	**ISO N**	**FS**	**# Elements**
6	4	-265	5.7	188377
13	14.5	110	12	187997
20	15.5	90	14	188836
40	5	-90	16	222228
50	14.5	-165	8.6	280854
56	29	-178	5.2	170602
60	39	-100	8.1	187954
71	57.5	50	12	147580
80	49.5	33	23	188775
91	16	10	128	191341

TABLE II
GAIT ANALYSIS, STREIFENEDER 3A20.

Gait Analysis Points, Streifeneder 3A20				
CYCLE	**ISO Deg**	**ISO N**	**FS**	**# Elements**
6	4	-265	2,5	311319
13	14,5	110	4	190708
20	15,5	90	5,2	147175
40	5	-90	7,9	214823
50	14,5	-165	2,1	213423
56	29	-178	2,1	216114
60	39	-100	2,3	174090
71	57,5	50	5,7	146361
80	49,5	33	8,3	217595
91	16	10	31	215203

As shown in Table II, the results of the simulations of the knee joint of the Streifeneder 3A20 brand with the maximum body mass of 100 kg, obtaining the maximum loads in intervals of 10% to 100% of the gait cycle. As the main result, the safety factors are determined, presenting a minimum value of 2.1 between 50 - 56% of the gait cycle with a load of 165 - 178 N and whose mesh is 216114 elements.

B. Main Parameters for the Design of Knee Prostheses

Table III shows the most relevant data obtained in different investigations, taking as a reference the age range with the most cases of people with lower-limb amputation between 20 to 64 years old, from these data, the minimum and maximum values of weight 56.63 kg and a 90.5 kg respectively, and stature has a minimum range of 156.9 cm and a maximum range of 176.6 cm [14]–[16].

TABLE III
ANTHROPOMETRIC DATA

Detail	**Age (years)**	**Weight (kg)**	**Height (cm)**
Center Rehabilitation Technical Aids. (with amputation)[16]	24 - 39	61,8-73,3	166,8-174,1
Center Rehabilitation Technical Aids. (without amputation)[16]	34,4 - 25,4	56,63-72,9	161,6-176,3
Caucasian ethnic groups from 61 surveys of Americans, Greeks, Czechoslovaks, Italians, Swedes, British, New Zealanders, Medeurs. (without amputación) [15]	21-36	61,9	173,5
Caucasian ethnic groups from 61 surveys of Americans, Greeks, Czechoslovaks, Italians, Swedes, British, New Zealanders, Medeurs. (without amputación) [15]	22-33	73	174,1
Hispanic, Non-Hispanic White, Non-Hispanic Black, Non-Hispanic Asian, Mexican American [14],[16]	20-59	73,39-79,1	161,8-163,4
Hispanic [14], [16]	20-59	74,25-76,7	157,3-158,9
Mexican americans [14], [16]	20-59	74,9-78,4	156,9-158,4
Hispanic, Non-Hispanic White, Non-Hispanic Black, Non-Hispanic Asian, Mexican American [14].	20-59	84,7-90,5	176-176,6
Hispanic [14], [16]	20-59	87,2-86,2	170,8-172,4
Mexican Americans [14], [16]	20-59	86,4-88,2	169,8-172,2

As shown in Table IV, anthropometric data was taken from the Prosthesis Imbabura foundation to corroborate with Table III.

C. Determination of the Target Population.

If the maximum and minimum values presented in Table III and Table IV are taken with reference, it can be said that the maximum body mass is 100 kg and the minimum weight is 42 kg, and the maximum height of 176 cm and minimum 153 cm, in an age range between 26 and 65 years in data obtained by a sample of 13 people who belong to the province of Imbabura.

TABLE IV
ANTHROPOMETRIC DATA [17].

Names	**Weight (kg)**	**Height (cm)**	**Age (years)**	**Use of prosthesis**	**Sex**
Edgar Flores	60	153	43	11 years	M
Robinson Folleco	100	176	41	24 years	W
Luis Foncea	85	172	65	9 years	M
Fabian Tates	81.6	165	58	10 years	M
Mario Guerrón	72.5	165	53	18 years	M
Rene Hidrobo	77.1	165	81	6 years	M
William Ipiales	72	164	26	3 meses	M
Jhonatan Risueño	65	170	16	6 años	M
Segundo Suarez	68	156	66	3 años	M
Gabriela Pozo	52	157	38	1 año y 7 meses	W
Mirian Torres	84	160	42	8 meses	W
Dayana Yepez	42	150	26	11 años	W
Judith Guerrero	52	150	56	2 años	W

IV. CONCLUSIONS

The ISO 14243-1 standard presents curves of the kinematics and kinetics of human gait that are useful for taking them to simulators and performing static and dynamic analyses since they present the different positions according to the human gait cycle the loads in each one of the trajectories. The main characteristics of the target population are body mass, height, and age, with a body mass ranging from 42 kg to 100 kg and height ranging from 153 cm to 176 cm for ages 26 to 65 years.

It is proposed to consider these ranges to make custom prostheses considering the main factor, such as body mass. Apply these loads to the human gait cycle and interactively modify the dimensions of the knee joint mechanism until an adequate safety factor is obtained. With these considerations, it is designed and simulated using 3D environments before going on to manufacturing, which could be through technologies such as 3D printing. Computational tools are an important key in developing personalized products since they allow parameterizing dimensional parameters obtaining unique products according to the characteristics of the person under study.

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