Nordic walking multibody analysis and experimental identification

Nordic Walking multibody analysis and experimental identification

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Abstract

The widespread diffusion of Nordic Walking as a trending sport discipline has increased the need for a tool to study the movement, both at the beginner and professional level. This paper presents a methodology for the analysis of the body motion during Nordic Walking. The main goal was to design a numerical tool able to replicate human body behaviour when performing this sport. With this approach, it is possible to study several biomechanical aspects, like the kinematics of each body segment, estimating loads applied to the joints for given tasks. Results can be used to compare the user movements with a standard technique implemented in the virtual environment. In fact, using a specific monitoring device developed in previous works, different parameters like the pole angle, arms cycle frequency and synchronization, as well as the pushing force applied to the ground, can be measured during the activity. This acquisition system can be used to save data to be compared with results from the standard numerical model, evaluating the user performance. In this work, numerical results were compared and discussed with measurements from the aforementioned device in terms of pole force and pole angle. The Ground Reaction Force obtained with the Multi-Body Model during Nordic Walking was then compared with results from the literature.

Keywords: Multibody dynamics, monitoring system, Nordic Walking, MEMS sensors, sport engineering

1. Introduction

Since the dawn of Nordic Walking (NW), numerous scientific studies have explored different aspects of this discipline, from the biomechanical analysis of the movement to its physiological implications. This sport can be considered an evolution of traditional walking. With the use of a specific pair of poles, the upper body is involved during the activity, which is the main feature of this technique. These characteristics were very interesting for Finnish professional skiers who started this discipline to train in the snowless period of the year.

Nordic Walking turns out to be beneficial to address several problems related to physical activity and can be defined as a sport suitable for people of all ages [1]. Several studies highlighted the benefits of Nordic Walking in terms of V_{O2} use, muscle training, heart rate, energy expenditure and other physiological parameters. An overall improvement of the aforementioned parameters during Nordic Walking was found in comparison to traditional walking[2–4]. The involvement of the upper body seems to be the main reason for the greater energy expenditure[5]. Also the effects of the correctness of the technique and how it affects physical benefits were investigated in the literature[6]. This last point makes Nordic Walking an interesting activity for rehabilitation especially for patients with cardiovascular problems, walking problems or Parkinson's disease[7–12].

From a biomechanical point of view, Nordic Walking is interesting for several reasons. It is difficult to identify the exact muscular activity depending on the spatial-temporal parameters of the gait cycle, as well as the applied load on the joints. In general, these studies do not reach the same conclusions, especially about the effects on the joints[13–16]. The authors agree that one of the reasons for these misalignments on the results may be related to the actual testing condition, as well as the different testing procedures considered. In fact, a standardized testing protocol is not available in the literature. Each protocol considered different testing characteristics, including the tester experience in Nordic Walking (instructor or not) and field sessions (indoor or outdoor), as well as different evaluation parameters of the activity. To allow outdoor/in field measurements of NW sessions, an integrated monitoring system was developed by the authors in previous works[17,18]. The authors considered the outdoor evaluation of the technique to be very relevant in the process of a better understanding of the athletic gesture. The device was designed to measure a set of parameters required to identify the athlete technique adopted during the activity session. An accelerometer was used to evaluate the number of walking cycle and angle of the poles during the contact phase. An integrated load cell measured the force applied on the pole and a GPS system tracked the user during the workout sessions. There are other research studies developing monitoring integrated systems, also in ski-sport[19–21]. The information given by this type of experimental set up can be compared to a multi-body model of a Nordic walker that is able to replicate the same body movements.

In the literature, several studies are available about the multibody (MTB) modelling of human walking, as well as skiing disciplines[22,23]. A multibody model allows one to simulate the dynamic behaviour of a mechanical system characterized by several rigid bodies connected with joints that affect their relative motions. This type of numerical analysis is usually considered when studying complex mechanisms and vehicle dynamics on different ground conditions[24–26]. In this work, a multibody model specific for Nordic Walking was developed to simulate a virtual environment for the same movements a user could perform in a standard session. Several hypotheses are required to model the human body and make it able to perform realistic movements during the simulation. Thus, a deep knowledge of the system studied is mandatory. At this stage, no muscle behaviour was simulated, instead focusing the attention on the system, rather than the subsystem performance. The humanoid model was developed to be parametric in order to replicate as much as possible the physical characteristics of the athlete that could affect the kinematic and dynamic behaviour of the numerical model in the simulation environment. An inverse kinematic approach was used, starting from a set of kinematic laws for the joints involved in the movement derived from experimental measurements available in the literature[27].

One of the goals of this work was to propose analytical and parametric expressions to describe the cyclic movement of the joints. The proposed mathematical laws were parametrized and generalized to be able to easily customize them to the movements of different testers. The main output of interest of the numerical model were the pole force and pole angle for a given set of kinematic laws. The simulated force and pole angle were then compared to the measured angles to validate the numerical model. The proposed parametric model was designed to allow for the analysis of the effect of different slopes (considering that the limit defined for Nordic Walking technique is approximately 10%) and ground properties. However, in this work, these two aspects were not considered. The attention in this study focused on Nordic Walking sessions performed and measured with the aforementioned acquisition device on a flat surface with the same ground properties, which were then replicated on the multibody environment. In this way, data measured and simulated could be compared given the same environmental conditions.

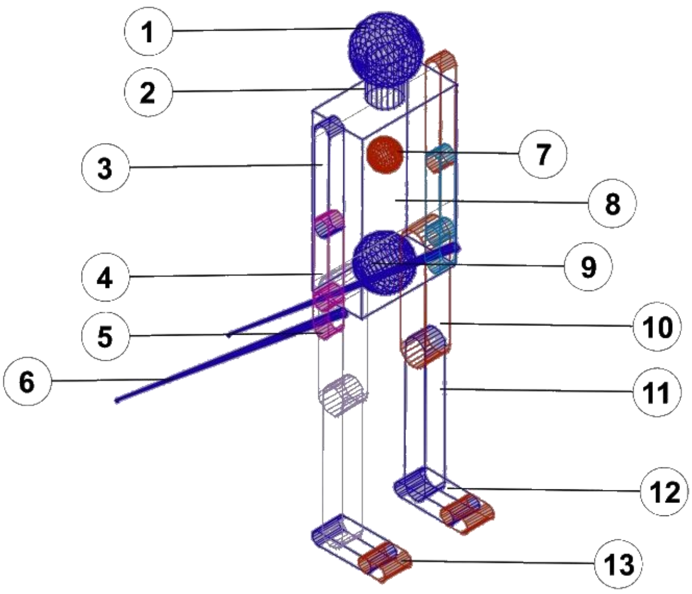
2. Methods

For Nordic Walking, as well as for other sport disciplines, the use of numerical models to simulate athlete movements provide useful tools to define and develop indicators for performance evaluation of a good Nordic Walker technique. Measurements coming from sensors placed on the athlete equipment and tools can be processed by these indicators to provide objective feedback on the performance. Moreover, a good estimation of not-measurable quantities, like the joints' forces and torque required to accomplish a certain task, can be obtained. In this work, the attention was focused on the development of the multibody model of a Nordic Walker. Several key points were addressed during the model development process:

- Development of a parametric model of the athlete human body
- Definition of the simulation strategy for the joint movements
- Modelling of the contact forces between the human body and the ground, as well as between the poles and the ground

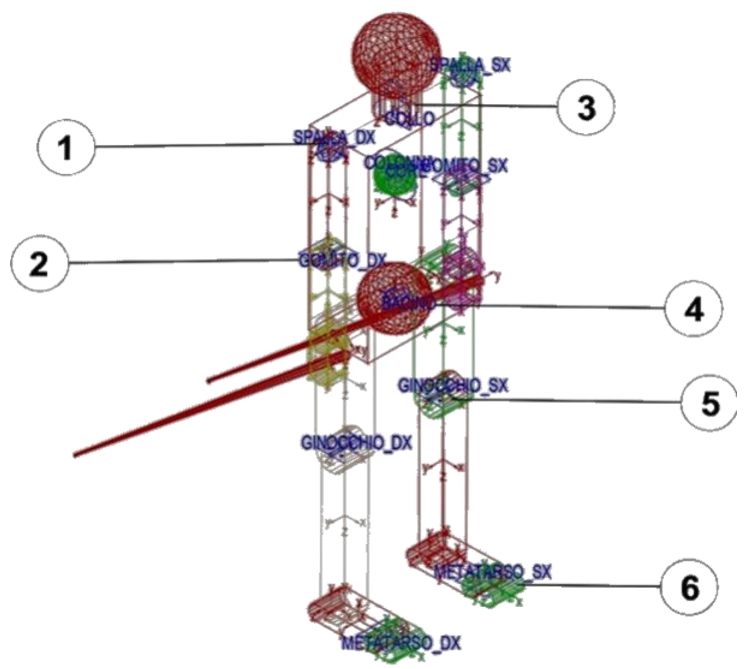
2.1. Parametric multibody modelling of the Nordic Walking athlete

The MTB model of a Nordic Walker athlete was developed within the MSC ADAMS environment. To simulate the human body and its joints, the model was built linking rigid bodies using different types of connectors organized to replicate the main Degrees of Freedom (DOFs) involved in the Nordic Walking movement. At this stage of the model, the effects of ligaments and cartilaginous tissues were neglected, but could be incorporated for a more detailed analysis. In Figs. 1 and 2, the humanoid bodies and joints modelled are shown, referencing each element to the corresponding part of the human body represented. Each rigid body was a simplified geometry of its real counterpart. However, each element was parametrized in terms of the total mass and total height of the humanoid as indicated in the literature[28,29] and reported in Table 1 (mass distribution) and Fig. 3 (geometric proportions). In this way, the inertia properties of each subsystem of the humanoid could be easily adapted to the characteristics of the athlete from which data are gathered. This point is crucial to relate some important parameters and indicators for Nordic Walking performance analysis to the real physical performance. As an example, the cycle time, which is usually considered as one of the most representative parameters, can assume a different meaning according to the total height, hence the leg leverage of the athlete.



Part number	Human body part	Rigid body
1	Head	Ellipsoid
2	Neck	Cylinder
3	Arms	Link
4	Forearms	Link
5	Hands	Link
6	Poles	Frustum+ Ellipsoid
7	Core	Ellipsoid
8	Trunk	Box
9	Pelvis	Ellipsoid
10	Thigh	Link
11	Shank	Link
12	Back foot	Link
13	Forefoot	Link

Figure 1 Humanoid model components



	Human body joints	Connectors	Degree of Freedom
1	Shoulder	Revolute	1
2	Elbow	Revolute	1
3	Neck	Fixed	0
4	Pelvis	Spherical	3
5	Knee	Revolute	1
6	Metatarsus	Revolute	1

Figure 2 Humanoid model joints

Table 1 Mass distribution on the human body

BODY PARTS	MEN [%]	WOMEN [%]
HANDS	1.3	1.0
FOREARMS	3.8	3.1
ARMS	6.6	6.0
FEET	2.9	2.4
THIGH	9.0	10.5
LEGS	21.0	23.0
TORSO	55.4	54.0

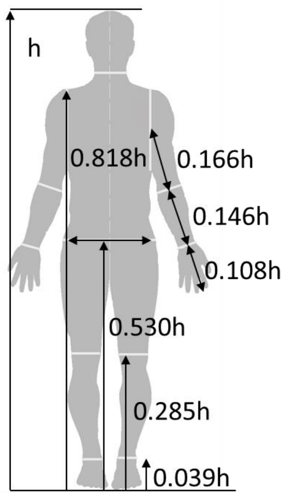


Figure 3 Body part lengths with respect to the total height

The ankle and hip were modelled using bushing elements which connect the bodies applying a series of forces and torques, defined by the damping and stiffness coefficients along the corresponding axes. Finally, a pair of poles were added to the humanoid model to include them in the Nordic Walking technique. These poles were also parametrized according to the total height of the athlete because its length must always be set to have a 90° angle between the arm and forearm[30,31], as ~~it~~ shown in Fig. 4.

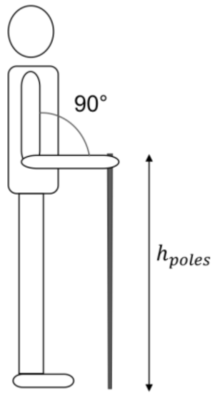


Figure 4 Correct height of poles

2.2. Joints kinematic laws

Following the inverse dynamic approach, kinematic laws were imposed as relative motion between the pair of bodies connected. The angular variation of each joint was introduced as kinematic constraint, using the "Motion" object in MSC ADAMS. The kinematic laws considered in this work were derived from experimental measurements available in the literature[27], where the angular variation of the lower limb joints (hip, knee and ankle) related to Nordic Walking sessions were shown. Considering the equations of motion of the lower limbs and how they were obtained in the literature, the equations of the upper body (shoulder, elbow) were derived accordingly. However, one of the aims of this work was to propose analytical and parametric expressions to describe the cyclic movement of the joints. Thus, from the time-angular displacement vectors of points for each measured joint motion, a Fourier Series expansion was evaluated to obtain periodic and continuous laws. According to the definition of Fourier Series, the equations of motions have all the same structure as shown in Eq. (1):

$$f(x) = a_0 + \sum_{i=1}^{n} a_i \cdot \cos(i \cdot \omega \cdot x) + b_i \cdot \mathrm{sen}(i \cdot \omega \cdot x) \tag{1}$$

where:

- $i = 0, \dots, n$ is the number of the harmonic;
- a_i and b_i are the real coefficients of the Fourier expansion;
- ω is the fundamental harmonic;

To obtain a better fit, each curve was evaluated with different multiples $i = 0, \dots, n$ of the fundamental harmonic. The main joints to which the equations of motion had been imposed were:

- Elbow
- Shoulder
- Knee
- Ankle
- Hip

Thus, the equations of the kinematic laws were written, modifying Eq. (1) with the form shown in Eq. (2):

$$f(x) = a_0 + \sum_{i=1}^{n} a_i \cdot \cos\left((time + K) \cdot \left(\frac{2\pi}{v}\right)\right) + b_i \cdot \text{sen}\left((time + K) \cdot \left(\frac{2\pi}{v}\right)\right) \quad (2)$$

where:

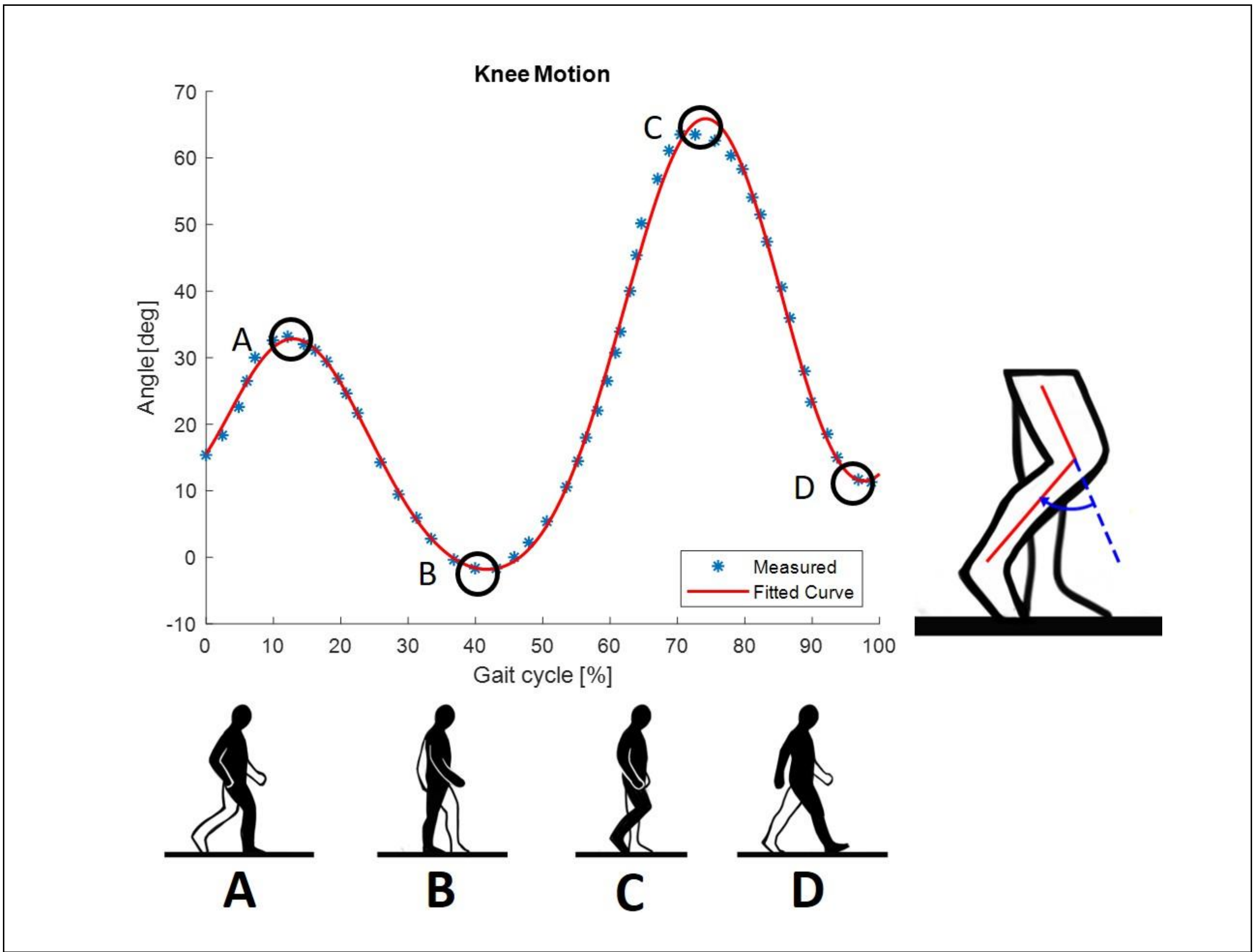
- $v = \frac{walking\ speed}{(2 \cdot amplitude\ of\ a\ foot\ step)}$
- $(2\pi/v)$ is the period of the function parametrized with the gait cycle
- $time + K$ represents a time shift of the time histories of the kinematic laws
- $K = \frac{\%cycle \cdot v}{100}$ is a percentage of the gait cycle

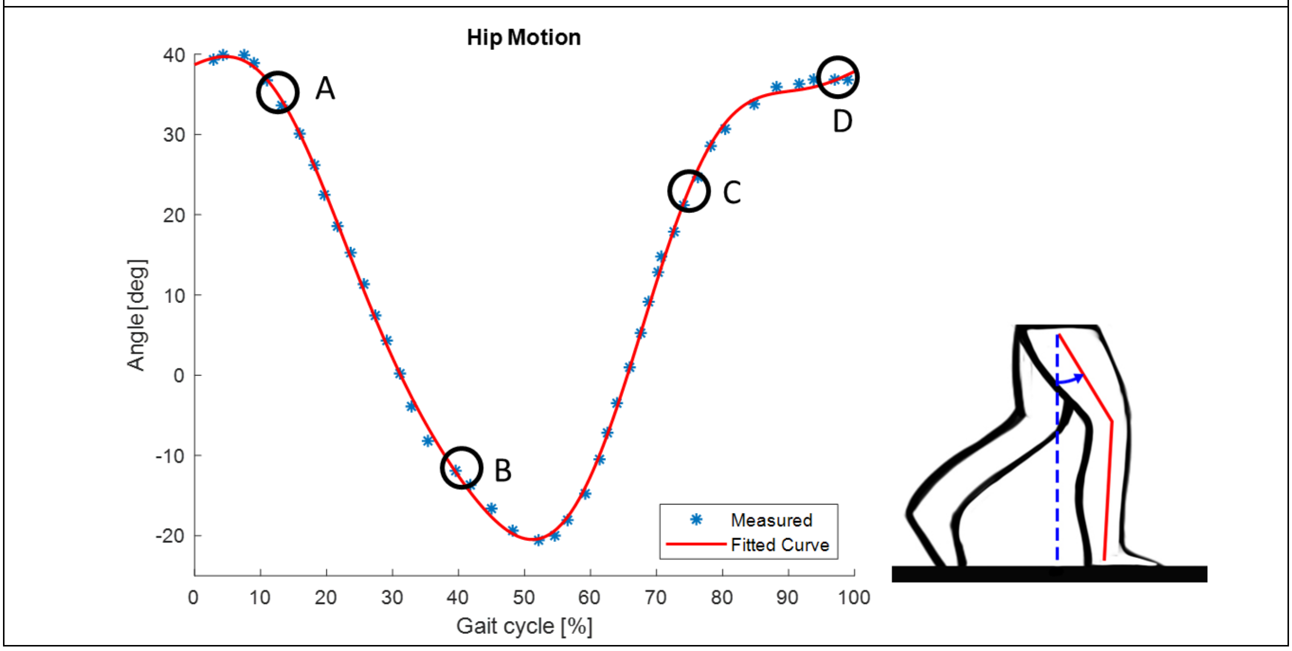
In Table 2, the real coefficients a_i and b_i of the Fourier expansion are reported for each joint. For each joint motion law, the mean error and standard deviation between the curves derived from the literature and their analytical expressions were evaluated. Results of this process are shown in Fig. 5 where the comparison between the curves from the literature and the analytical representations are shown. In Table 3, the indicators of this fitting problem show a good approximation obtained with the Fourier representation.

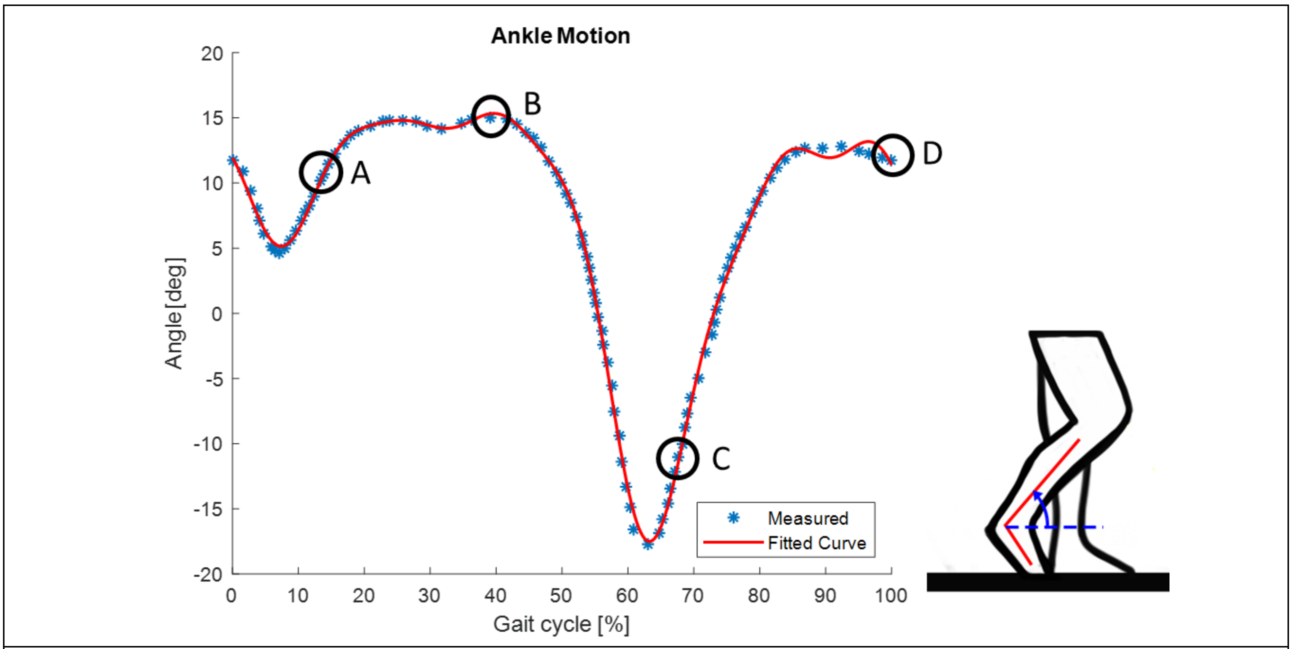
All the joint motions were introduced according to this formulation because of the parametrization with respect to the mean walking speed. In this way, using the same structure for the kinematic laws, several analyses can be performed at different average speeds. This is of course a simplification of the problem since the technique changes with respect to the performance to be achieved. However, for most of the users, the technique should not differ much from the nominal/correct one. Moreover, the parametrization allows to easily fit experimental measurements of joint motions and make them suitable for numerical simulations.

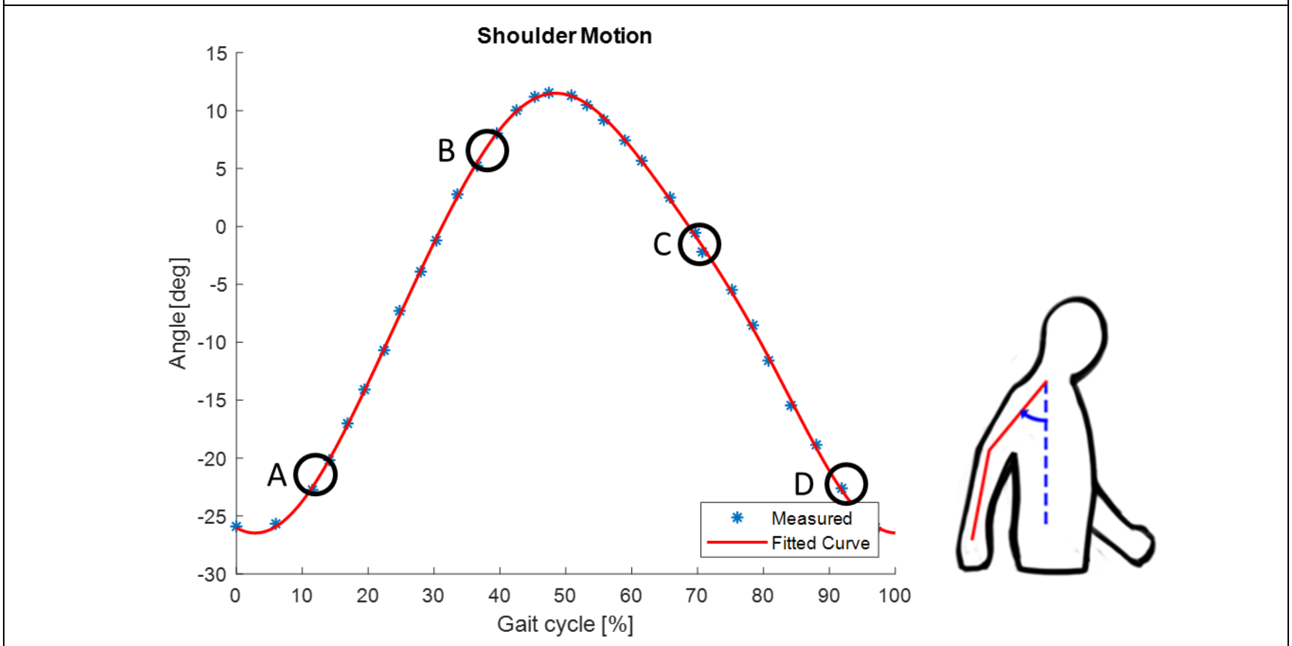
Table 2 Coefficients of the Fourier expansion

Coefficients of the Fourier expansion	Hip	Knee	Ankle	Shoulder	Elbow
a_0	13.83	25.22	7.47	-6.61	43
a_1	29.82	4.90	3.64	-18.17	-19.36
b_1	-5.08	-18.79	7.90	-2.26	-4.62
a_2	-4.72	-14.51	1.59	-0.65	3.59
b_2	1.43	13.45	-8.04	-1.30	0.40
a_3	-0.23	-0.057	-3.83	-0.59	0.34
b_3	2.71	5.57	-0.10	-0.019	-0.65
a_4	-	-	2.45	-	-
b_4	-	-	-0.23	-	-
a_5	-	-	0.11	-	-
b_5	-	-	-1.50	-	-


Knee Motion
Angle [deg]
Gait cycle [%]
Measured
Fitted Curve
A
B
C
D


Hip Motion
Angle [deg]
Gait cycle [%]
Measured
Fitted Curve
A
B
C
D


Ankle Motion
Angle [deg]
Gait cycle [%]
20
15
10
5
0
-5
-10
-15
-20
0
10
20
30
40
50
60
70
80
90
100
A
B
C
D
Measured
Fitted Curve


Shoulder Motion
Angle [deg]
Gait cycle [%]
15
10
5
0
-5
-10
-15
-20
-25
-30
0
10
20
30
40
50
60
70
80
90
100
A
B
C
D
Measured
Fitted Curve

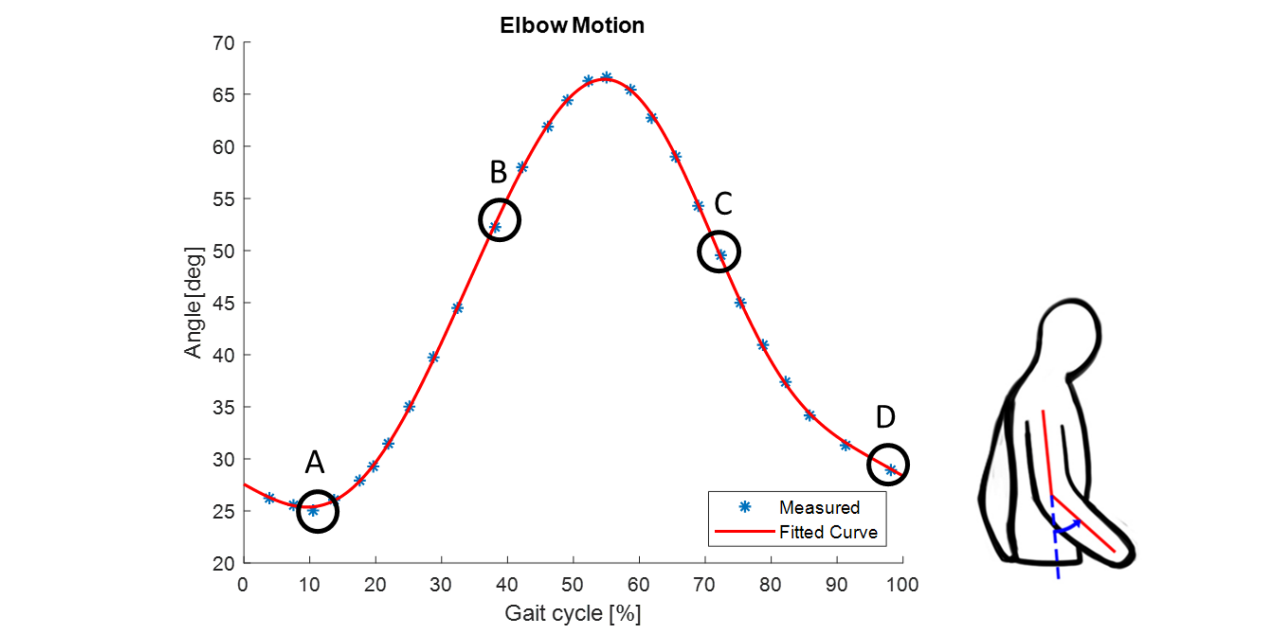


Figure 5 Comparison between joint motions and their fitting functions

Table 3 Fitting performance of the Fourier expressions

Joints	% Mean Error	% Standard Deviation
Hip	0.028	0.089
Knee	-0.017	0.239
Ankle	-0.0166	0.96
Shoulder	-0.007	0.088
Elbow	2.067e-05	0.005

2.3. Ground contact model

Contact forces were simulated in MSC ADAMS using the definition of the "Nonlinear Hertz Contact Model"[32] using the formula shown in Eq. (3):

$$F_N = k \cdot d^e \ [N] \tag{3}$$

In MSC ADAMS, this formula was defined as an impact force with the following expression (4):

$$IMPACT(x, \dot{x}, x_1, k, e, c_{max}, d) \tag{4}$$

where:

- x was the distance variable;
- $\dot{x}$ was the time derivative of x, so the velocity;
- x_1 was a positive real variable related to the free length of x. If x was less than x_1, then a positive value for the force was determined. Otherwise, the force value is zero.

These parameters were computed at each time step during the simulation and they were strictly connected with the geometry. The following parameters were instead defined by the user:

- k was the contact stiffness;
- d was the distance, after that the full damping coefficient was applied;
- e was the exponent of the force;
- c was the damping coefficient.

To define the contact forces between the ground and the foot, it was necessary to introduce the corresponding values of the equivalent stiffness (K) and damping (C). These values couldn't be obtained from the literature or from the experimental activity. To approach this issue, a sensitivity analysis was developed. So in this work, the influence of the stiffness and damping, as inputs to the model, on the changes of the output of the model was studied. The outputs of interest were the Ground Reaction Force (GRF) and the penetration of the feet into the ground (penetration depth). The GRF was defined as the force acting between the ground and the foot during the Stance Phase of the walking gait cycle, while the penetration depth was the measure of the distance between the centre of mass of the back foot and the surface of the ground.

To develop this analysis, two target values for the output parameters were chosen:

1) The optimal value for the GRF was defined as shown in Eq. (5):

$$GRF_{th} = 1.4 \cdot mass \cdot g \ \ [N] \tag{5}$$

The value of GRF_{th} is known in literature[16,33]. From this value and the GRF obtained from the simulation, the deviation was measured through the expression shown in Eq. (6):

$$\%deviation = \left(\frac{GRF_{th} - GRF}{GRF_{th}}\right) \tag{6}$$

The threshold value for the penetration of the feet in the ground was defined as s < 2.5 cm. This value was assumed by the authors as a reasonable first approximation, considering the sum of the deformation of the ground, sole of the shoes and the foot. The stiffness and the damping of the soil were defined to better describe the ground characteristics of the environment, where the measurements of the Nordic Walking sessions were taken. The influence of different ground conditions (like grass, rocks, etc.) were not considered in this model, but could be implemented in future works thanks to the parametric approach of the contact model.

The two output parameters, the GRF and ~~the~~ Penetration Depth, shown in Fig. 6, were computed for each simulation, first keeping constant the stiffness and varying the damping, then varying the stiffness and keeping damping constant.

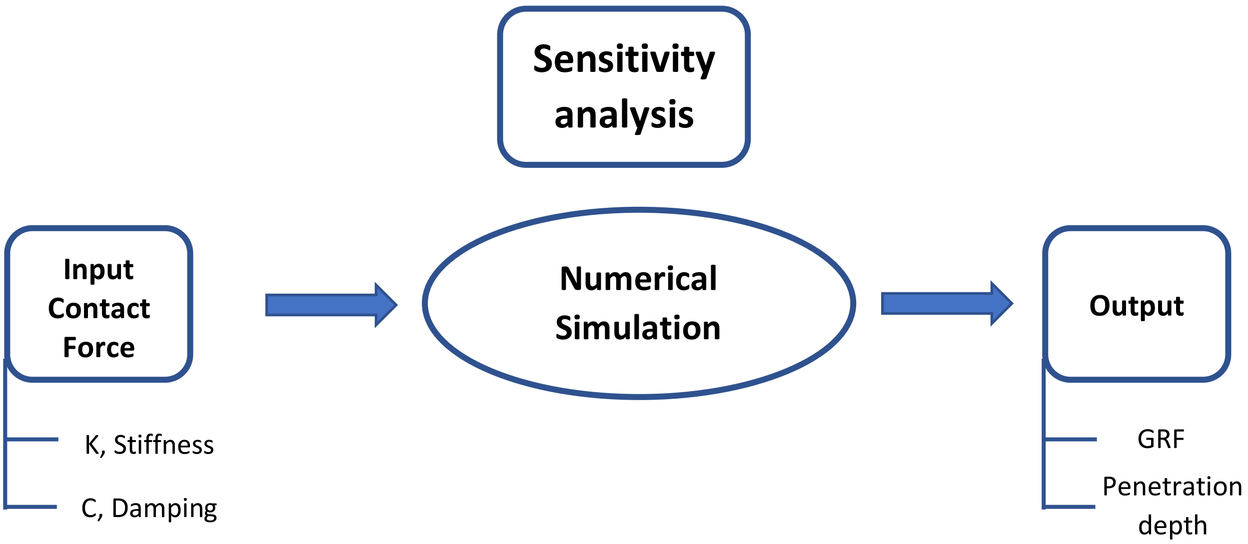


Figure 6 Sensitivity analysis workflow

This analysis was performed to obtain the variation trend of the two quantities (Figs. 7 and 8). In conclusion, using this method, it was possible to obtain the values of stiffness and damping to be introduced in the definition of contact force that allowed for a representative numerical simulation. The results obtained from the simulation with these values, in terms of percentage deviation and the penetration depth of the feet in the ground, were always below the threshold values and close to the optimal one.

To manage the contact between the pole tip and the ground, it was assumed that the deformation of one of the two bodies (the tip of the pole) was negligible compared to the deformation of the second (the ground). This assumption is particularly true if the poles are used on soil, grass and other soft terrains where the deformation of the ground is much higher than the deformation of the pole tips. More detailed analyses are required for contact with stiffer floors compared to pole tips.

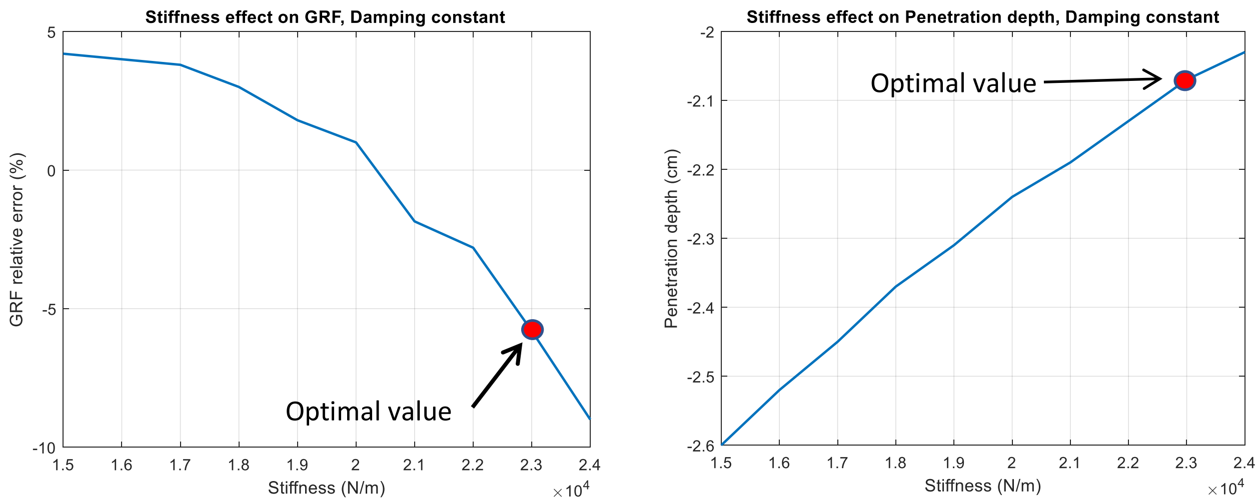


Figure 7 Sensitivity analysis: stiffness effects on GRF and penetration depth

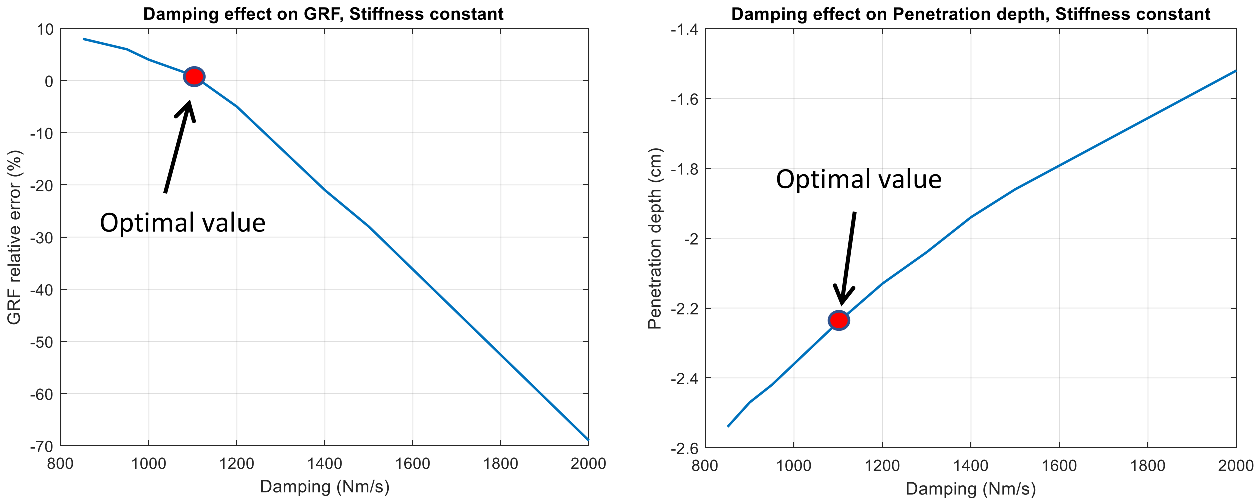


Figure 8 Sensitivity analysis: damping effects on GRF and penetration depth

3. Simulation and Results

The analysis performed with the numerical model focused on two main aspects: a numerical-experimental comparison and a literature-numerical comparison. On one hand, the first part includes the comparison between the numerical the experimental pole force, as well as the comparison between the pole angle evaluated on the MTB and the one measured experimentally. Then, a qualitative comparison of the GRF with the data available in the literature is shown to validate the contact model.

3.1. Numerical and experimental pole force comparison

To validate the proposed Nordic Walker model, a comparison between the measured pole force applied to the ground for a given Nordic session and the simulated one was performed. This analysis used the analytic kinematic laws obtained in the previous sections to replicate the movements performed during the experimental measurements. To be clear, the authors were aware that the tester movements were surely slightly different from the simulated laws. The assumption made in this work was that the technique of the tester was close enough and comparable with the technique of the model that was obtained from kinematic laws. Thus, the force and kinematic quantities measured with the monitoring platform could be compared to the results obtained for a Nordic Walking session kinematic laws.

The humanoid model was adapted to the people who performed the monitored Nordic Walking sessions. The experimental test session was performed with four Nordic Walkers and the Multibody simulation was adapted to their physical characteristics. The test was performed by monitoring a thirty-step indoor path and the four subjects were asked to maintain a constant speed. The results obtained from this first analysis are shown in Fig. 9. The numerical force showed a similar behaviour compared to the measured force for the different testers. Assuming a time cycle of one second, the contact phase occupies almost half of the total cycle. In terms of timing, both the measured and simulated pole's peak occurred during the mid-pushing phase, as is shown in the literature[17,18]. In Nordic Walking, the Contact Phase is the time during which the pole is in contact with the ground. This phase includes the impact and the pushing phase. The first phase is when the pole touches the ground and the force starts to increase. The pushing phase is when the force reaches the peak and then starts decreasing. These phases are shown in Fig. 10. Although a slightly different time evolution was observed, the same trends were confirmed. Evaluating the integral of the force for the four testers, the impulse obtained as shown in Eqs. (7) and (8):

$$I_{experimental} = \int_{t_0}^{t_1} F(t)dt \tag{7}$$

$$I_{numerical} = \int_{t_0}^{t_1} F(t)dt \tag{8}$$

show comparable results between the experimental and numerical values as reported in Table 4.

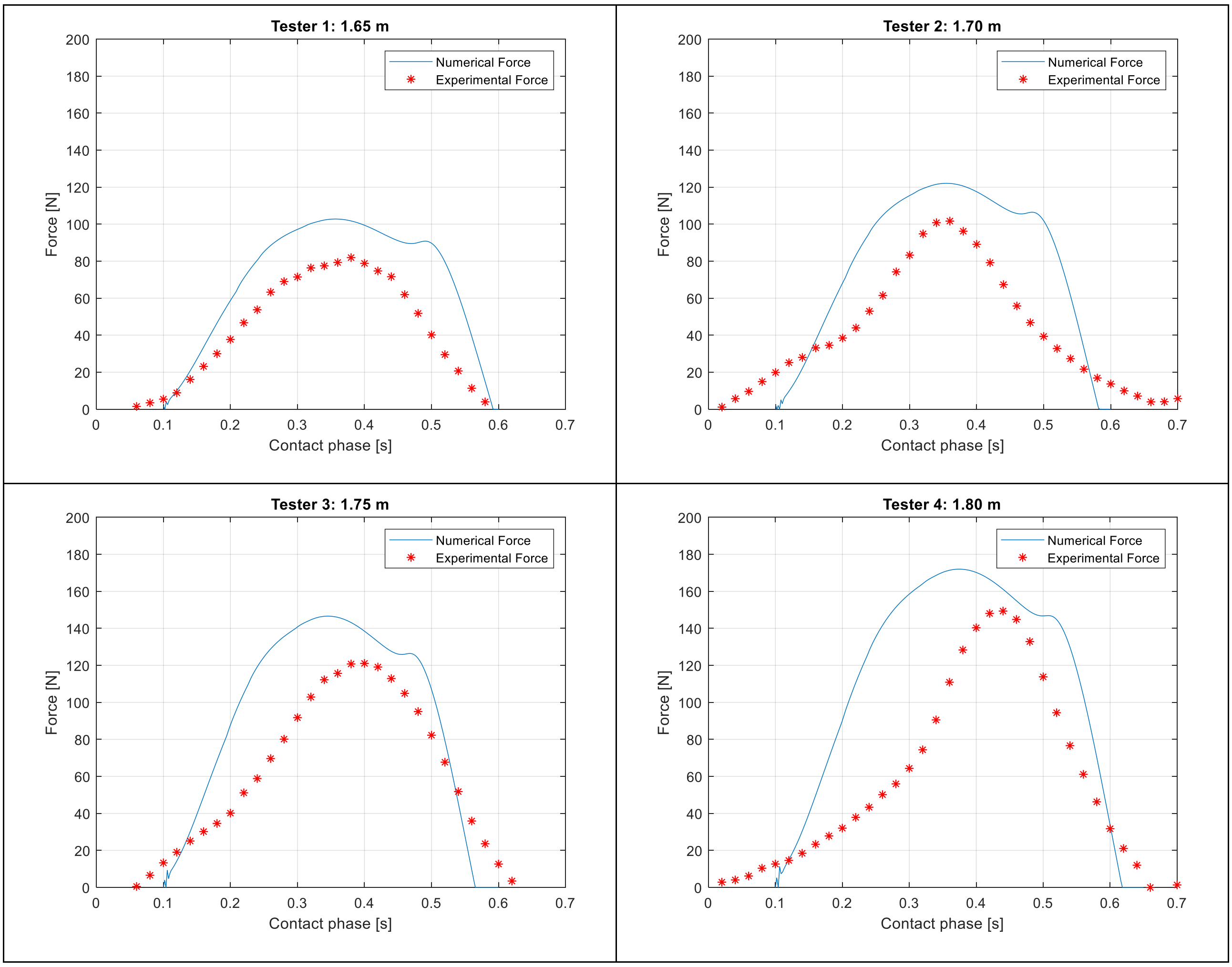


Figure 9 Numerical Pole Force varying the height and weight

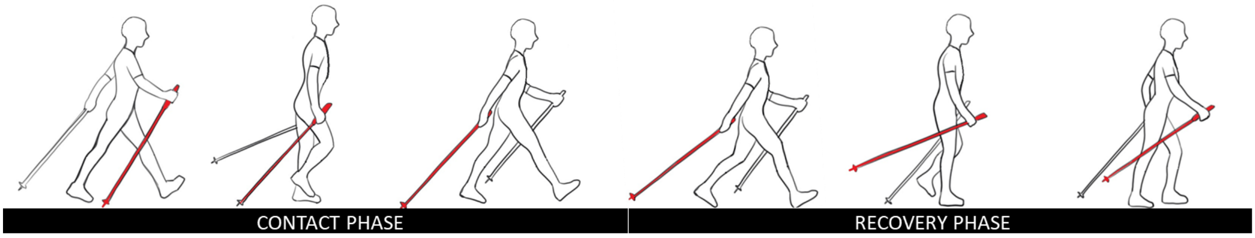


Figure 10 Pole force comparison: Simulation vs Experimental Results

Table 4 Average impulse of the Pole Force for Numerical and Experimental results

Height [m]	Mass [kg]	$I_{numerical}[Ns]$	$I_{experimental}\ [Ns]$
1.65	65	35	23
1.70	70	40	29
1.75	75	47	35
1.80	80	60	40

Thus, despite the two curves showing slightly different patterns, the similar trend and peak values translated to comparable values of the impulse, which is the most interesting quantity, especially if energy analysis must be performed. Concerning the different slopes of the approach and egress phase during the contact phase of the overall Nordic Walking, these can be related to the overall stiffness of the measurement system comprising the load cell and the real pole and to the real kinematic laws of the Nordic Walker. In the numerical simulation, the poles are approximated with a rigid body, thus the force increases rapidly when the humanoid wants to push on the pole. Moreover, the approximation of the kinematic laws imposed on the upper body joints, especially the wrist and the elbow joints, strongly affects the final shape of the contact force. Thus, the attention focused on replicating the overall pushing behaviour instead of replicating the exact shape of the pushing force. Figure 10 shows the pole force obtained from the MTB simulation for the four cases evaluated and the impulse obtained in these cases were collected as shown in Table 4. The values reported in the table are the average values of the impulse during all the Nordic Walking sessions developed for the test.

3.2 Pole angle analysis

An additional comparison of the experimental data and numerical simulation is developed between the measured pole angle and pole angle obtained from the MTB simulation. The experimental pole angle is evaluated during the contact phase, when the tip pole is in contact with the ground. During the impact phase, the evaluation of the angle can only be hypothesized, rather than be calculated numerically by the acceleration due to the dynamic component of the accelerations acting at that time and the vibrations due to the impact itself.

As discussed by Mocera et al.[17], it is possible to estimate the angle between the pole and the ground with the formula shown in Eq. (9):

$$\vartheta = arcos(a_x) \tag{9}$$

where:

- a_x is the acceleration along the x-axis of the pole (the reference axes are shown in Fig. 11)

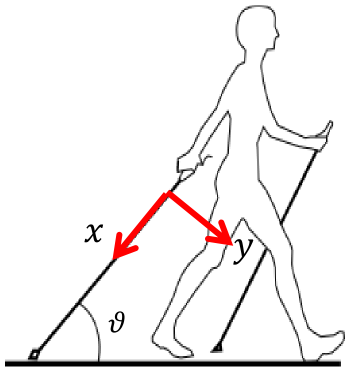


Figure 11 Pole angle

This equation assumes that the deviation from the sagittal plane is small enough to accept the approximation of the pole angle, not considering the angle on the frontal plane. The computation of the pole angle (ϑ) is possible only when the pole is in contact with the ground, and when the disturbs due to the impact reduced their effect. These considerations were confirmed in the authors previous work [17,18].

The overlap of three experimental data sets with the pole angle obtained from the simulation is shown in Fig. 12. What was obtained was the same trend of the Multibody simulations during the phase when the contact angle was evaluated with the measurement device. To obtain the experimental data, the same experimental set up used in the previous test was performed. It was noted that the influence on the angle of the mass or the height of the athlete was low. Figure 12 shows the pole angle for a 1.80 m tall tester, but the same results were obtained from the other tester. The variability in the experimental data depends on how the poles impact the ground, which was obviously different on each cycle of the same Nordic Walking session.

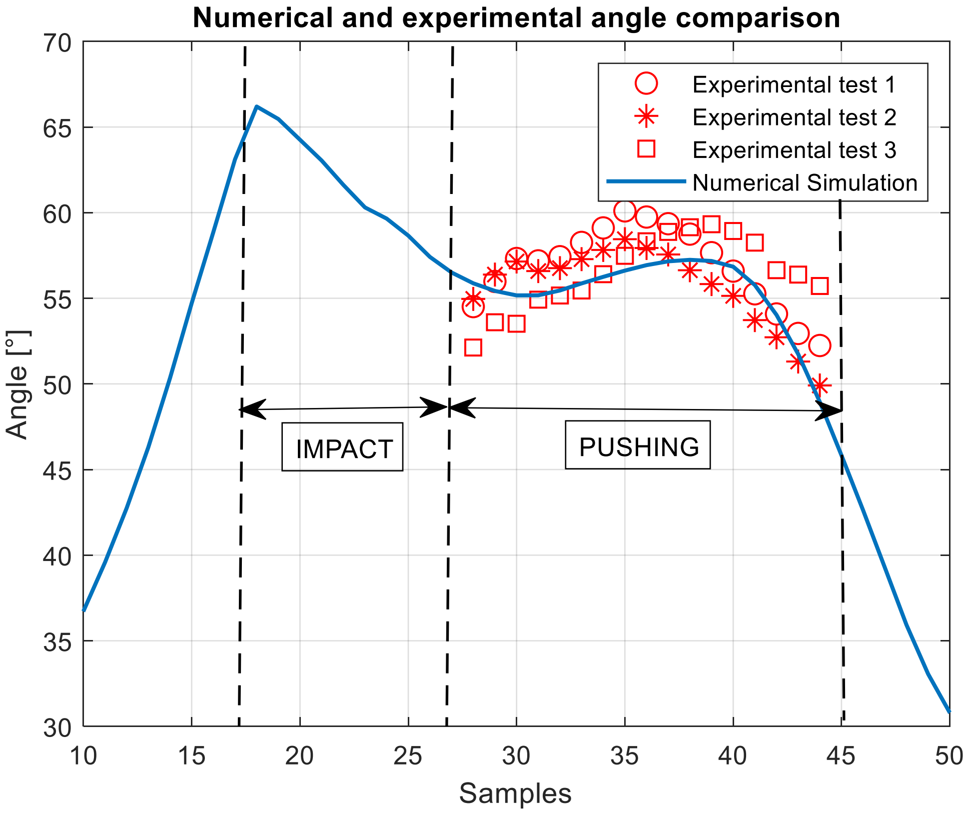


Figure 12 Numerical and Experimental angle comparison

3.3 Ground Reaction Force Analysis

From this preliminary analysis, it was possible to obtain the GRF trend during the stance phase of the cycle or the part of the cycle when the single foot was in contact with the ground. In Fig. 13, the trend of the GRF for a model with a height of 1.75 m, weight of 75 kg and average walking velocity of 1.6 m/s is shown. The dotted line represents the theoretical curve of the GRF derived from literature analysis[27] for an athlete of the same size and mass. The numerical curve has the same trend as the theoretical curve and the value of the two peaks are very similar.

In detail, the first peaks theoretical and numerical equations are shown below as Eq. (10) and Eq. (11), respectively:

$$First\ peak_{theoretical} = 140\% \cdot total\ weight = 1030\ [N] \tag{10}$$

$$First\ peak_{numerical} = 1070\ [N] \tag{11}$$

with a percentage of the relative error as shown in Eq. (12):

$$\% = \left(\frac{First\ peak_{th} - First\ peak_{num}}{First\ peak_{th}}\right) = -3.7\% \tag{12}$$

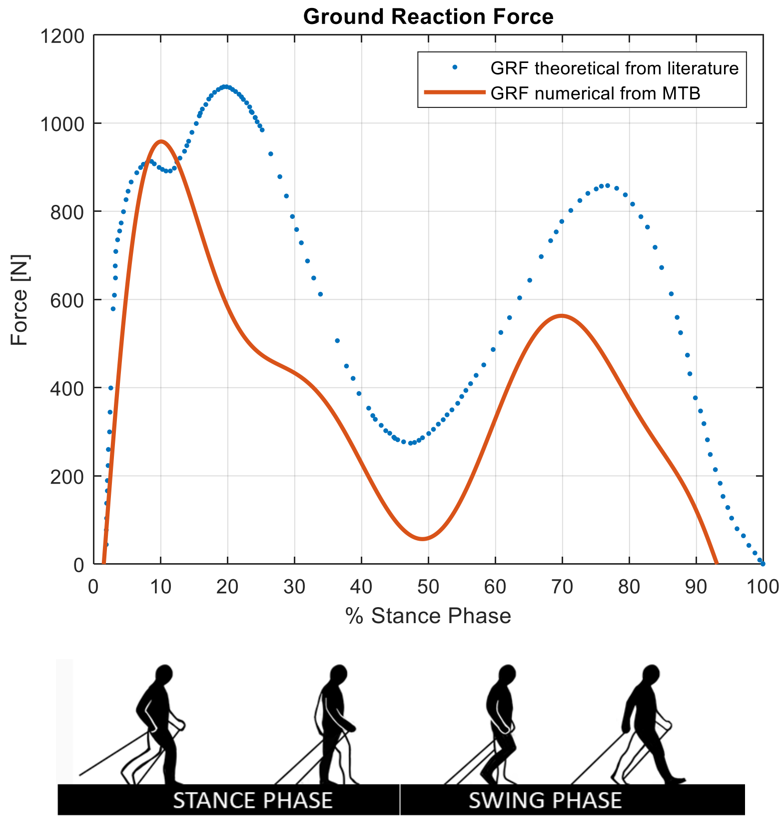


Figure 13 Ground reaction force behaviour comparison between experimental from literature[27] and MTB

The analysis was performed for different athlete profiles in terms of mass and height with the same parameters used for the previous analysis. As shown in Table 5, the relative error on the peak GRF was always well below the 5% error, which means that the sensitivity analysis performed led to balanced values for the stiffness and damping parameters of the contact model between the humanoid and ground. The purpose of this analysis was to verify that the comparison in terms of peak values and trend between the numerical curve and the experimental curve was as close as possible and to verify the stiffness and damping, seen in the previous paragraph, used to model the contact between the foot and the ground.

Table 5 GRF analysis for different athlete profiles

Height [m]	Mass [kg]	GRF numerical (MTB) [N]	GRF experimental [N]	Relative error
1.65	65	925	893	-4%
1.70	70	954	961	1%
1.75	75	1070	1030	-4%
1.80	80	1080	1099	2%

4 Conclusions

In this paper, the development of a multibody model to simulate the Nordic Walking activity was shown. This work represents the second phase of the research started with the design of a monitoring system to measure Nordic Walking parameters illustrated in previous works by the authors. A Multi Body model helps to estimate mechanical quantities, like forces and torques, acting on the main joints of the human body as a consequence of performing specific movements. Moreover, in future works, the numerical environment will allow for the study of different environmental conditions (in particular ground characteristics) thanks to the design approach used. The developed model was designed parametrizing both the humanoid model and the pole length to allow for different types of users. Moreover, this work proposes some mathematical parametric representations of the kinematic laws of the main joints of the human body during Nordic Walking. The parametric laws used in this work were obtained from measurements available in the literature. However, they can fit new experimental data to easily implement these motions inside a numerical simulation. The obtained numerical model was compared with measured experimental data, as well as with literature data, to validate trends and representative values of the quantities. The model showed good agreement in terms of pole forces when considering several body characteristics. The model also compared favorably to the pole angle obtained during the sessions. Finally, a qualitative comparison of the Ground Reaction Force evaluated on the numerical model was performed against values available in the literature. Trends and peak values were obtained also in the numerical model considering that no indications were available about the exact kinematic laws related to the GRF values taken as references. Thus, the MTB model showed overall good results in representing the Nordic Walking technique in a simulation environment. Future works will consider the analysis of the same quantities on different ground conditions to understand their effects on the amount of force required to accomplish certain types of movements.

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