Biomechanical Analysis and Gait Assessment for Normal and Braced Legs

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Abstract— In this work an attempt is made to derive suitable models to investigate the effect of the joints constrained on human gait due to wearing bracing devices at lower limbs. Linkages concept are used to model the leg segments and evaluate GRF and friction force. Three models for normal, AFO and KAFO are presented. The presented models are semi analytic since some input data are needed to be evaluated experimentally. In this regard the joint angles are evaluated from video analysis of individual walking on Treadmill. KINOVEA program is used to track the joints angles for the stance phase of gait cycle, and the MATLAB program is used to estimate the angular displacement as a function of time. To validate the results some experiments on force plate were conducted for the three mentioned cases. The results showed good agreements and that the suggested models are succeeded for describing the human gait parameters for normal and abnormal gait.

Index Term— Ankle Foot Orthosis AFO, Knee Ankle Foot Orthosis KAFO, Ground Reaction Force GRF, Normal Gait.

I. INTRODUCTION

In normal leg the locomotive action is achieved due to the contribution of the leg muscles which supply moments to rotate the leg segments. In view of kinematics, the segments undergo rotational velocities and accelerations about the joints. However for braced leg such as AFO and KAFO some joints are locked and constrain the rotation. In view of kinetic, the rotations sequence produce the ground reaction force GRF and friction force between feet and ground. These forces are various with the stride. In general normal gait gives a slender curve profile of forces which is useful for assessment the gait cycle. In other hand the deviation of the force curves indicate the abnormality due to pathology or disability. The relation-ship between the movement change and the force change for all movement forms are given by using motion laws for Newton’s. Thus, use two techniques, experimental and mathematical, to measurement the movement force for musculoskeletal system. Where, the mathematical techniques are used for evaluating the effect for various difficult parameters which cannot be evaluated with experimental techniques, [1].

The biomechanical analysis investigations of the same subject done by many researchers with various ways are presented as follows:

Marina U. McCulloch, (1993), [2], investigated the speeds walking effect for foot orthotics on the angular changes of knee and ankle. Thus, the evaluated results are investigated with respect to the effect of a bio-mechanical.

After that time, at (1998), C. R. Wren et. al, [3], investigated the body physical state for motion of human. Where, the investigation was done using mathematical techniques to evaluate the behavior of system with various system parameters effect. Then, at (2009), Tea Marasovic et. al, [4], investigated the locomotion for systematic and gait analysis. Where, the investigation was included using the bioengineering techniques to evaluate many characterizations for gait with various analysis, kinetic and kinematic analysis.

Also, at (2015), Sadiq J. Abass et. al, [5], studied the gait cycle effect on the dynamic human walking. Where, the analysis included is used for force plate and digital camera for the measurement of the level-walking. Where, using Skill-Spector software, ver. 1.2.4, to evaluate the data for kinematic and using Matlab to evaluate the Pedottidiagram.

Finally, at (2017) M. A. Al-Shammar et. al, [6], presented a new composite materials for using in a prosthesis socket to modify the mechanical properties and the fatigue life for sockets. Where, the investigation included experimental technique measurement the mechanical properties and fatigue life for new composite materials used. In addition, the experimental technique include measurement of the interface pressure distribution, and then, comparison its pressure results with analytical pressure results.

In addition, the ankle foot orthosis, knee ankle foot orthosis and other subject to biomechanical application are presented by more researchers, where, M. J. Jweeg, K. K. Resan, and other researchers at (2010 to 2017), [7-20], presented multi studies about this subject. Also, the applications of biomechanical are investigated and modified for the materials used, where, more materials, used at its application, are composite materials. Therefore, the modified composite materials are presented by many researchers and applied for various engineering applications. As, Muhannad Al-Waily et. al, at (2005 to 2017), [21-51], presented the modified composite materials by different reinforcement materials and types and also presented the effect of improvement materials on various application at the foot and socket.

Finally, M. R. Ismail et. al, presented dynamic transfer function for below-knee using experimental techniques and comparison with theoretical technique, (2017), [52], where, the investigation studied for SID method to analyze the parametric study for below-knee prosthesis leg. Then, at (2018), [53], they investigated the fitting for self-suspension of below-knee by using mathematical techniques with various parameters effect for socket and gait cycle on the fitting.
There are some contraindications for AFO that helped the researchers to use it as a rusticator not as a corrector. The AFO blocks range of motion ROM of ankle joint and foot. Therefore, may be excessive if orthotic objective does not require blocking plantar flexion, dorsiflexion, and inversion/eversion. Slows down forward progression, Knee flexion/foot flat moment produced at heel strike/Perry’s first rocker and Fair quadriceps strength is required if set in dorsiflexion.

II. MATHEMATICAL MODEL
The presented theoretical models are based on the kinematic and kinetic analysis of linkages. It is assumed that the leg segments are rigid and the variations in angular velocities at the joints are negligible. Three models for normal and with using AFO and KAFO will be derived.

II.1. Normal Leg Model
Fig. 1, shows the schematic representation of linkage model of normal leg. In this model the links OA, AK, KH and HC are for foot, shank, thigh and trunk respectively. The horizontal and vertical coordinates unit vectors are \( e_1 \) and \( e_2 \). The angles of various joints are \( \Phi \) and measured from the horizontal line they are positive at clockwise direction. The external forces subjected to the foot which are friction and GRF are denoted by \( F_F \) and \( F_G \). Point C is the body center of gravity from which the body weight is located.

Now using the dynamics of rigid body one can derive the acceleration at the ankle joint as the follows,

\[
a^A = a^O + \alpha_f \times r^{A/O} + \omega_f \times (\omega_f \times r^{A/O})
\]  

(1)

Where, \( \omega_f \) and \( \alpha_f \) are the angular velocity and acceleration of the foot and the displacement vector. \( r^{A/O} \) (From A to O) is,

\[
r^{A/O} = l_f(-\cos \Phi_f e_1 + \sin \Phi_f e_2)
\]  

(2)

In the similar way the acceleration of Knee joint can be written as,

\[
a^K = a^A + \alpha_t \times r^{K/A} + \omega_t \times (\omega_t \times r^{K/A})
\]  

(3)

Where \( \omega_t \) and \( \alpha_t \) are the angular velocity and acceleration of the lower leg and:

\[
r^{K/A} = l_t(\cos \Phi_t e_1 + \sin \Phi_t e_2)
\]  

(4)

Finally, the acceleration of Hip joint can be written as,

\[
a^H = a^K + \alpha_t \times r^{H/K} + \omega_t \times (\omega_t \times r^{H/K})
\]  

(5)

II.2. AFO Orthosis Model
Fig. 2, shows sketch of AFO orthosis model in this case the Ankle joint is constrained so that no relative motion occurs. Now for the Knee joint one can write the acceleration as the follows,

\[
a^K = a^O + \alpha_f \times r^{K/O} + \omega_f \times (\omega_f \times r^{K/O})
\]  

(6)

Where;

\[
r^{K/O} = l_f(-\cos \Phi_f e_1 + \sin \Phi_f e_2)
\]  

(7)

For hip joint the acceleration is defined in Eq. 5 and, \( r^{H/K} \) is defined in Eq.6.

II.3. KAFO Orthosis Model
Fig. 3, shows sketch of KAFO orthosis model in this case the Knee joint is constrained so that no relative motion occurs. Now for the Ankle joint one can write the acceleration as follows,

\[
a^A = a^O + \alpha_f \times r^{A/O} + \omega_f \times (\omega_f \times r^{A/O})
\]  

(8)

Where, \( \omega_1 \) and \( \alpha_1 \) are the angular velocity and acceleration of the lower leg and;
Where,
\[ r_{A/O} = l_f (\cos \phi_f e_1 + \sin \phi_f e_2) \]  (12)

For Hip joint the acceleration is;
\[ a^H = a^A + \alpha l \times r^{H/A} + \omega_1 \times (\omega_1 \times r^{H/A}) \]  (13)

Where,
\[ r^{H/A} = (l_i + l_f)(\cos \phi_i + \sin \phi_i) \]  (14)

The GRF and friction force can be evaluated from Eqs. 7, 8.

For Hip joint the acceleration is;
\[ a^H = a^A + \alpha l \times r^{H/A} + \omega_1 \times (\omega_1 \times r^{H/A}) \]  (13)

Where,
\[ r^{H/A} = (l_i + l_f)(\cos \phi_i + \sin \phi_i) \]  (14)

The GRF and friction force can be evaluated from Eqs. 7, 8.

II.4. Motion Analysis via KINOVEA
KINOVEA is video analysis software. In this work KINOVEA program was used to track and measure the angle of the lower limb joints for the three cases. Treadmill is used for test the walking of individual. Marks are supplied for joints for tracking the joint motions. The following procedures are followed in using the program,
1. Preparing the proper video length.
2. Making the required scaling and calibration to insure real measuring.
3. Selecting a number of frames (key images) to measure the angle for each joint.
4. After completing the program all the measured data of joints are automatically saved in Excel file format.
5. The same procedure is repeated for AFO and KAFO cases. It is to be mention here that, only stance phase of the gait cycle is considered since GRF and friction forces are existed due to the contact with the ground.

II.5. Anthropometry Data
The participial is female 62 kg body mass and 158 cm tallness. According to these data the required mass and length of each segment are evaluated from Table I. In case of using AFO and KAFO an additional masses are added which are:0.263 kg, and 1.493 kg for AFO and KAFO mass, respectively.

### Table I

<table>
<thead>
<tr>
<th>Segment</th>
<th>Length % BL</th>
<th>Mass % BM</th>
<th>CG(Px) % Seg. Len.</th>
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<td>Head &amp; neck</td>
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III. EXPERIMENTAL INVESTIGATION

The main step of the experimental work is the manufacturing process of the AFO and KAFO used in the testing, treadmill walking test and force plate for measuring GRF and friction force.

III.1. Manufacturing of Orthosis
Two orthosis were prepared for experimental testing which are, rigid polypropylene ankle foot orthosis and metal side bars knee ankle foot orthosis.

III.1.1. Manufacturing of AFO
The general steps for manufacturing of AFO were,
A. Taking the measurements, these are; circumference of the calf, circumference around the malleoli bone, the length from the knee to the ground, length of foot and the width of the heel and metatarsal bone.
B. Casting process includes the placing of the plastic tube and applying the cotton sock above it. Soaking the role of plaster with water and rolling it on the whole leg from top to the foot, while doing this step trying as possible to make the leg at the right anatomical posture. The angle between the foot and leg is 90 deg. and the leg stand still. By Hand the areas of bony protrusions were identified and highlighted wait until the mold getting little harder and then cut it from a mid-line above the plastic tube, remove the mold from the patient leg and prepare the mixture of water and powder plaster and fill the mold with it, finally give time to the cast to harden and then start sculpturing it.
C. Sculpturing, prepare the tools: tape measures, serfumer, plaster roll, knife. The first step is opening the mold and removes it from the cast. Begin with removing the thin layer from the cast. locating the bony prominent and build the walls of the caste from the medial and lateral sides, build the bottom surface of the foot and build the rocker bar, smoothen the cast and take it to the polypropylene molding room, as shown in Fig. 4.
C. Sculpturing: the tools,
- Tape measures, serfum, plaster roll, knife.
- The first step is opening the mold and removing it from the cast, begin with removing the thin layer from the cast, locating the bony prominent and built the walls of the caste from the medial and lateral sides, built the bottom surface of the foot and built the rocker bar, smoothen the cast and take it to the polypropylene molding room.

D. Polypropylene draping and vacuum molding: Cut the sheet of polypropylene on our measurements and adding 2 cm length and width, heat the sheet at 180° for 20 min depending on the sheet thickness. Drop the polypropylene over the mold and without stretching it to tightly, stick it together along the anterior side, tight the sheet and open the vacuum, with scissors cut the excess polypropylene, cut it with cutter and remove it from the mold.

E. Refining the trim lines and placing tapes: after cutting the shape of the orthosis, start to refine the edges and trim lines, placing the tapes on at the whole orthosis on the calf area and the foot, as shown in Fig. 5.

III.1.2. Manufacturing of KAFO Orthosis

The manufacturing process includes the following,

A. Taking the measurements, Thigh circumference under the great trochanter, Mid-thigh circumference, Circumference around the knee joint, circumference of the calf, circumference around the malleoli bone, the length of thigh, the length from the knee to the ground, length of foot, width of the heel and metatarsal bone.

B. Casting process: first placing the plastic tube and apply the cotton sock above it, soak the role of plaster with water and start to roll it on the whole leg from top to the foot, while doing this step trying to as possible make the leg at the right anatomical posture, insure that the angle between the foot and leg is 90 deg. and the leg stand still, By Hand identify and highlight areas of bony protrusions and also make the mold and coherent and smooth, wait until the mold fitting little harder and then cut it from a mid-line above the plastic tube, remove the mold from the patient leg and prepare the mixture of water and powder plaster and fill the mold with it, give time to the cast to hardens and then start sculpturing it.

D. Polypropylene draping and vacuum molding: Cut the sheet of polypropylene on our measurements and adding 2 cm length and width, heat the sheet at 180° for 20 min depending on the sheet thickness, drop the polypropylene over the mold and without stretching it too tightly, stick it together along the anterior side, tight the sheet and open the vacuum valve, with scissors cut the excess polypropylene, draw the shape of the two parts of the KAFO with the cutter and remove it from the mold.

E. Side bars placing: these bars are made from metal structure, and covered with leather at points where body contact occurs and act as bearing supports. This orthosis consists of a rigid femoral stem and a calf foot part made of polyethylene or polypropylene, in some cases, leather can be used. A joint - locked or not - connects the two parts together, depending on the case, double-sided or single-sided high-rise. It is held with Velcro closures and the shoe. The most important step in this kind of orthosis is locating the place of the knee and determine horizontal axis of the knee joint. Then modify the columns by meanders leg, Fig. 6.

G. Alignment and Biomechanics: The alignment of the KAFO orthosis is performed by adjusting the horizontal axis of the knee joint and the ankle joint, the misalignment can be detected by letting the patient wear the device and walking and observing the fixation of the deformity. In view of biomechanics: the correction depends on GRF force action line. So that the weakness of the lower limb can be overcome by the correction action of KAFO which can support the Y ligament action at the hip ambulation. The alignments process is shown in Fig. 7.
III.2. Gait Analysis
In the second step of the experimental work, the treadmill device was used and adjusted on a speed near the normal speed of the gait cycle for the chosen case, as shown in Fig. 8. Firstly, each individual have his own gait pattern and walking speed so we have to test a range of speeds and choose the one which is normal and uncomfortable, in this case the chosen speed was 2.8 m/min. Before beginning of the tests the scale is adjusted and markers on the three joints are placed finally the video for was recorded for Kinovea analysis.

Fig. 8. Treadmill for Gait Analysis.

Fig. 9. Angle Measuring for Normal Gait

IV. RESULTS AND DISCUSSION
The results of Ankle, Knee and Hip angles (in degree) for normal leg after using Kinovea are collected in Table II. The data of these tables are used for evaluating the best fitting equation by using MATLAB (Rb2013a). The angular velocity and angular acceleration for the foot, lower leg and thigh then derived by differentiation one and twice, respectively. For the two orthosis Tables III and IV are constructed.

<table>
<thead>
<tr>
<th>Key Image</th>
<th>Time Sec</th>
<th>Ankle (deg.)</th>
<th>Knee (deg.)</th>
<th>Hip (deg.)</th>
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Table III

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Fig. 9. Angle Measuring for Normal Gait

III.3. Force Plate Test
The aim of using the force plate is to measure the forces during the stance phase in order to make a compression between the theoretical and experimental results. The three cases are investigated where the GRF are measured.

III.4. Kinovea Analysis
In order to analyzing the gait cycle the image and video processing is used. Kinovea is one of the available software which is more effective. In this program some key images are extracted for selected events in stance and swing phases for each image the absolute angles of Ankle, Knee and Hip were measured for each cases by using angle measuring tools as shown in Fig. 9.
Fourth degree polynomial equations are used which gave a good fitted curves since the $R^2$ values are approaching to 1. The various obtained fitting equations and the associated $R^2$ are as the following.

### A. Normal leg,
1. Ankle, for, $R^2$: 0.9866,
$$\phi(t) = - (8.721e^{-6}t^4 - 0.0003088 t^3 + 0.003729 t^2 - 0.01824 t + 0.03086)$$
2. Knee, for, $R^2$: 0.9673,
$$\phi(t) = (-6.501e^{-6}t^4 + 0.0002942 t^3 - 0.004383 t^2 - 0.000554t + 1.676)$$
3. Hip, for, $R^2$: 0.9938,
$$\phi(t) = - (-1.223e^{-6}t^4 + 0.0001487 t^3 - 0.004331 t^2 + 0.06232 t + 1.313)$$

### B. AFO Orthosis,
1. Knee, for, $R^2$: 0.9868,
$$\phi(t) = - (-2.429e^{-6}t^4 + 0.0001772 t^3 - 0.002831 t^2 + 0.01464 t - 0.01493)$$
2. Hip, for, $R^2$: 0.9591,
$$\phi(t) = - (-6.74e^{-6}t^4 + 0.0003645 t^3 - 0.005394 t^2 + 0.02608 t - 0.02738)$$

### C. KAFO Orthosis,
1. Ankle, for, $R^2$: 0.9969,
$$\phi(t) = (4.116e^{-7}t^6 + 2.431e^{-5}t^3 - 0.001587 t^2 - 0.007764 t + 1.946)$$
2. Hip, for, $R^2$: 0.9702,
$$\phi(t) = (5.116e^{-7}t^6 + 3.431e^{-5}t^3 - 0.00220 t^2 - 0.007764 t + 1.946)$$

Figs. 10 and 11 give the theoretical values of GRF and friction force for normal leg. Figs. 12 and 13 give the values of GRF and friction force for AFO case. Figs. 14 and 15 give the values of GRF and friction force for KAFO case.

The experimental results of the force plate for the GRF and friction force for the three cases are shown in Figs. 16 to 21. From the comparison between the theoretical and experimental results it can be seen that the trend of the force curves are nearly identical. However there are some errors between the two curves, these errors may be attributed due to the following reasons,

1. The theoretical linkage models considered only the motion in sagittal plane however in real there are some effects of motion in other plans such as frontal and transverse.
2. The different in the ground interfacing Martials used in analyzing motion when using treadmill and that for the force plate.
3. The errors due to the using of curve fitting equation for calculating the angular displacement, velocity and acceleration for Hip, Knee and Ankle.

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<th>Angles(deg)</th>
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Fig. 13. Theoretical Friction Force for AFO.

Fig. 14. Theoretical GRF for KAFO.

Fig. 15. Theoretical Friction Force for KAFO.

Fig. 16. GRF Results of Force Plate for Normal Gait.

Fig. 17. Friction Force of Force Plate for Normal Leg.

Fig. 18. GRF of Force Plate for AFO.

Fig. 19. Friction Force of Force Plate for AFO.

Fig. 20. GRF of Force Plate for KAFO.
V. CONCLUSION

From the theoretical and experimental results and the comparison between them, the following conclusions can be derived.

1. The theoretical results of GRF force are in a good agreement with the experimental results.
2. The theoretical results of friction force are not agree with the experiments this is due to the difference of the material type between the treadmill and force plate work.
3. The variations of both GRF and friction force for AFO and KAFO orthosis are different as compared with the normal leg, this is due to the constrained effect of the orthosis on the joints ROM.
4. The presented linkage model can serve as a simple and powerful tool for evaluation of normal and abnormal gait without the need of complicated testing tools.

REFERENCES


