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Comparison between Metallic and Allograft Knee Prosthesis Using Musculoskeletal Modeling

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The objective of this paper was to test the applicability of the model introduced by Eltoukhy and Asfour (2010) in the gait analysis of subjects with joint replacements and to show that the model can be used for applications such as surgery planning. The case study selected in this research was the total knee replacement surgery, which involved subjects with two different knee joint types, namely, metallic and allograft. The gait patterns of the two groups were compared against normal subjects (control group).

A total of fifteen subjects participated in this study, five subjects in each group. Based on the statistical analysis conducted it was evident that the allograft group had less significant gait deviations than did those in the metallic group. In particular, the metallic group patients had greater gait deviations both in the loading-response phase, and in the Fore-Aft terminal stance phase.In conclusion, our findings suggest that implantation of hinged total knee prosthesis with removal of one or two of the quadriceps muscles provide good functional results during gait. Additional studies should be performed to evaluate the relationship between the number and extent of the quadriceps heads excised and both the knee mechanics during gait and the long-term survival of the prosthesis.

A comparison between the gait results obtained using the developed musculoskeletal model and the results obtained from the experimental research conducted by Benedettiet al. (2000) clearly indicate that the model predicts gait parameters for individuals with knee replacement in a highly accurate manner. The model could prove to be a valuable tool that enables surgeons to visually evaluate different knee replacement surgery strategies.

Keywords: *Musculoskeletal Modeling, Total Knee Replacement, Gait Analysis.*

1. INTRODUCTION

1.1. Gait Analysis

Clinical Gait Analysis is a tool used to quantify multi-planar motion of both normal and pathologic gait in an objective fashion. It is often used to guide decision-making on management in such disorders as cerebral palsy, stroke and traumatic brain injury, among others. Because of the complexity and expense of the test, gait analysis is primarily used as part of the surgical decision-making process when all conservative treatments have been exhausted and surgical intervention is being considered.

Gait analysis provides a unique opportunity to obtain objective information that cannot be obtained through other clinical means. Improvement in gait after multi-level surgery using kinematic data has been documented (Steinwender *et al.* 2000).While kinematics provides information on dynamic joint motion, kinetics is essential for differentiating between primary deformities and secondary responses (Gage, 1993).

1.2. Musculoskeletal Modeling

Three-dimensional (3D) computer modeling possesses the advantage of providing useful insights and allowing the 3D-evaluation of the behavior of individual muscles during the different human movements. As it has been shown by a number of researchers such asAlkjaer et al. (2001), 3D vectors better represent the line of action of the different muscles as compared to two-dimensional (2D) vectors specially when investigating the location of both the origin and insertion of muscles.

One of the important applications of the computer modeling of human body is the area of joint replacement where a validated model can be used for instant surgery planning. It is known that the evolution of total knee and total hip replacement has been influenced to a great extent by the knowledge obtained from gait analysis studies (Andriacchi and Hurwitz, 1997). Many of the mechanical problems associated with these devices have been evaluated in terms of the mechanics of walking where the magnitude and pattern of the forces at the hip and knee joints obtained from gait analysis studies have been used as design criteria of both total hip and total knee replacements (Andriacchi and Hurwitz, 1997). Because of the additional forces induced by muscles, knowledge of how the muscle forces are applied can be very important for understanding the bone strength and degeneration around the replacement so that replacement joints can be designed and tested with the loading environment in which they will operate.Fortunately, computer modeling can provide useful insights for human biomechanics (Nagano *et al.* 2005). Most in-vivo experiments only reveal the forces in the joint and not the surrounding muscle forces or their point of application. It is also known that finding the internal forces in the body by in-vivo experiments alone is difficult and sometimes impossible.

A number of studies have been conducted to investigate the forces in the different joints in the lower extremities. For instance, with regard to hip joint, a number of studies have been conducted to validate musculoskeletal models using both instrumented hip replacements (Bergmann *et al.*, 2001, Brand *et al.*, 1994) and the activity levels of muscles obtained by means of electromyography (Crowninshield *et al.*, 1978). Others have studied the forces produced in the knee joint (Piazza *et al.*, 1996), and the ankle joint (Orendurff *et al.*, 2002).

While these studies have shown that the hip contact forces and muscle activity levels can be represented by computational methods andseveral theories have been developed subsequently (Crowninshield *et al.*, 1978, Rasmussen *et al.*, 2001), the question of how the body recruits the muscles for a given activity needs more understanding. This question can be better answered through the use of 3D musculoskeltalmodelling. Using three-dimensional computer modelling makes it possible to evaluate the behaviour of individual muscles during various human movements (Eltoukhy&Asfour, 2009 and Yamaguchi, 2001).

1.3. Knee Replacement

According to the American Academy of Orthopaedic Surgeons, there are about 270,000 knee replacement operations performed each year in the United States. Although about 70% of these operations are performed in people over the age of 65, a growing number of knee replacements are being done in younger patients.Knee replacement is basically a surgery for people with severe knee damage during which the surgeon removes damaged cartilage and bone from the surface of the knee joint and replaces them with a metal and plastic surface (Figure 1). In other words, it involves the resurfacing of the worn out parts of the knee using a metal component on the end of the femur and the top of the tibia, with a plastic bearing in between. The total knee replacement had been studied in the literature by a large number of researchers. One of the most relevant studies to this research paper was the study conducted by Benedetti *et al.* (2000) and that is because of the similarities between the two studies, werethe subjects, almost the same sample size, suffered from the same type of tumor and performed the same type of activity (walking). In their study the authorsdetermined the gait function as it relates to the residual quadriceps' strength and to the specific components of the quadriceps removed in patients treated with total knee replacement.

Figure 1: Total knee replacement surgery

2. METHODOLOGY

2.1. Subjects and Procedures

Five male volunteers with no history or complaints of known walking problems, knee injuries and postural instability participated in this experiment as the control group.

Ten male patient subjects was the maximum number that was available to participate in this study. All patient subjects had distal femoral knee replacement surgery. Five subjects were allograft patients while the other five were metallic patients. The Following table summarizes the demographicsof all three subject groups.

Table 1
Demographicsof Subjects

	Control	*Metallic*	*Allograft*
No of Subjects	5	5	5
Age (years)	26.6 ±0.9	42.3 ±5.9	28.6 ±5.6
Height (cm)	175.8 ±1.9	175.8 ±8.5	163.0 ± 8.0
Weight (kg)	71.8±3.9	89.6±15.5	66.0±8.3

The procedures performed on the study subjects were wide local excision of the malignant bonetumor and reconstruction using either a Stryker (tm) MRS rotating hinged knee or an osteoarticular allograft. The MRS knee was placed after radical resection of the distal femur. The distal femur was prepared by reaming the intramedullary canal with the appropriate sized reamer to achieve the greatest diameter stem with an appropriate cement mantle (2mm circumferential). The tibia was prepared with standard cutting jigs.

The tibial and femoral canals were filled with cement after pulse irrigation. The components were segmental and prepared on the back table to reconstruct the longitudinal dimensions of the defect. The components were assembled using inner bearings an axle and rotating metal hinge. In some cases, a gastrocnemius flap was turned up into the defect to fill the dead space and to help tether the lateral pull of the extensor mechanism. The allografts were prepared differently.

The patient's menisci and portions of the lateral, medial collateral ligaments along with the anterior and posterior cruciate ligaments were retained. The allograft was aseptically harvested from a suitable donor; the cartilage was preserved with DMSO and frozen in a controlled fashion to -80 degrees for storage. In the operating theatre, this preselected graft was then thawed in lactated ringer solution and cut on the back table to the appropriate length. A plate or plates were then affixed to the graft and the soft tissue structures were then reconstructed.

The reconstruction began with the posterior capsule followed by the posterior cruciate, the lateral collateral ligaments and finally the anterior cruciate ligament. The meniscofemoral attachments to the allograft were repaired following this. The graft itself was then anchored to the patient's host bone with plates and screws.

The participants were given instructions including an explanation of the test procedures, proper attire, and the expected duration of the testing. The data was collected at the University of Miami Biomechanics Research Laboratory, USA, with an approval from the Internal Review Board (IRB). 48 reflective markers were placed at the different body land marks (e.g. joints centre lines and segments).

First, a static trial was conducted where the patient stands at a tee pose which is then used for markers labeling. Then five dynamics trials were performed. Each subject was instructed to walk at his normal walking speed (3 miles per hour on average) across the laboratory and on top of the four force plates (Figure 2).

2.2. Instrumentation and Data Collection

The laboratory incorporates a ViconNexus® Motion Capturing System (Oxford Metrics, United Kingdom). The motion capturing system integrates and synchronizes four Kistler force plates (Model: 9253B), ten MX cameras, two high speed reference video cameras, and wireless Noraxon EMG system. The MX cameras provide 1024 x 1024 pixel resolution and frame rates up to 250 Hz. The setup including the force plates and the MX cameras is shown in figure 3.

The MX cameras capture the reflected infrared light from the markers placed on the subject's landmarks and thus the X, Y, and Z coordinates of the body segments and joints at the different time steps are recorded continuously. The reconstructed data output of the motion capturing session is shown in figure 4, which depicts the stick figure of the subject's lower extremity, the reflective markers as recorded by the MX cameras, the segments' center lines and reference frames, and the ground reaction vectors acting on the subject.

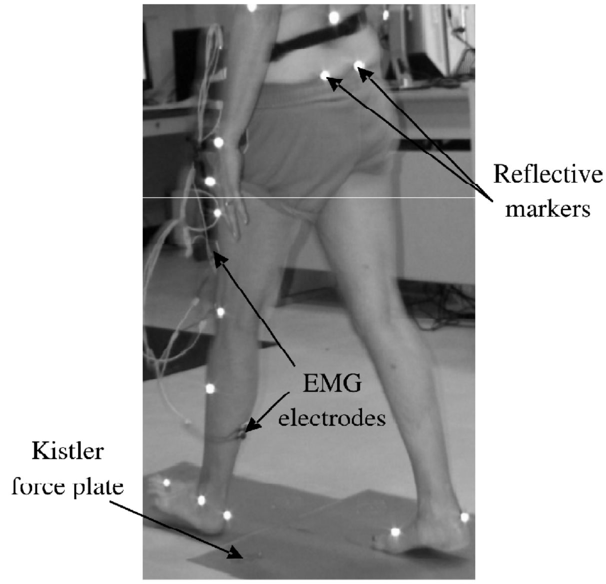


Figure 2: Actual subject walking across the lab during a gait motion capturing session

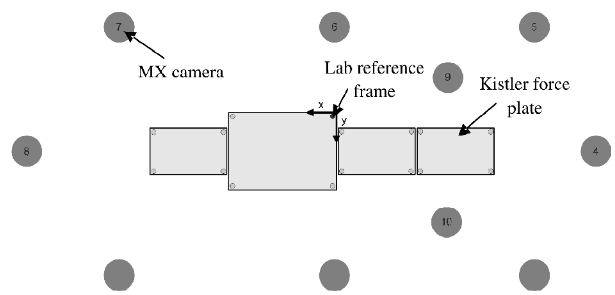


Figure 3: Force Plates and Cameras Configurations

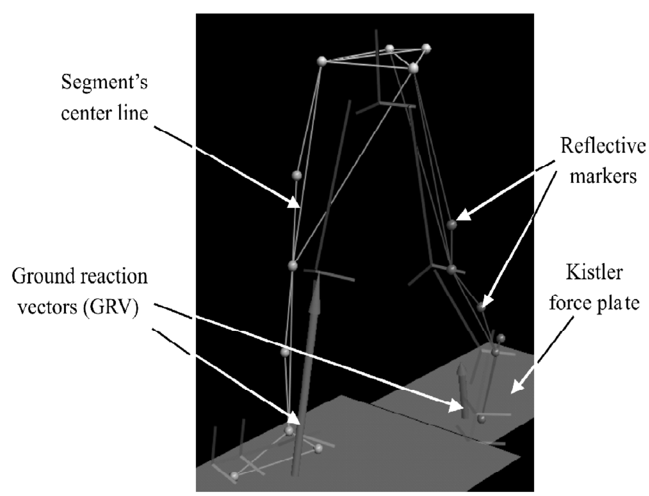


Figure 4: Lower extremity stick figure and ground reaction vectors with labeled markers and reconstructed segment's center lines

2.3. 3D Lower Extremity Musculoskeletal Model

Once the motion capturing data was reconstructed and all gaps were filled then the C3D file, which contains the X, Y, and Z coordinates of the different markers as well as the force plate data, is imported to the 3D lower extremity modelling phase.The three-dimensional musculoskeletal model of the lower extremity introduced by Eltoukhy and Asfour (2010) was utilized in this study. The model consisted of seven rigid body segments connected with frictionless joints, these segments are the pelvis, right and left thighs, right and left shanks and right and left feet. Hip joints were modeled as universal joints that have three degrees of freedom. Knee joints were modeled as hinge joints, while ankle joints were modeled as biaxial joints. Hip joint flexion/extension, adduction/abduction and internal/external rotation as well as ankle joint dorsi/plantar flexion and inversion/eversion were all allowed (Figure 5). The model is scalable to the subject's dimensions; with 27 muscles in each leg been included, the exact origin and insertion points as well as the different muscle parameters are all added in the model as well.

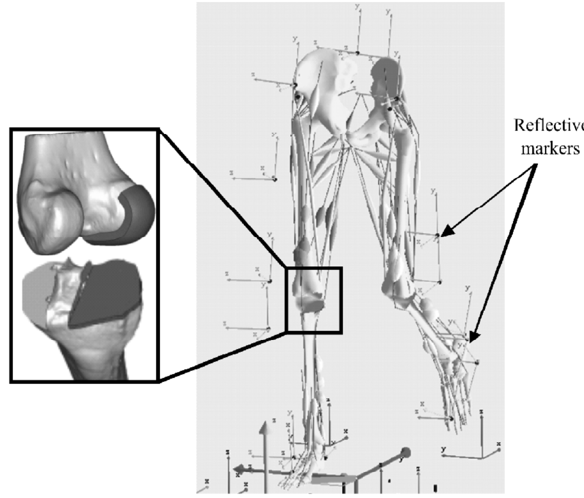
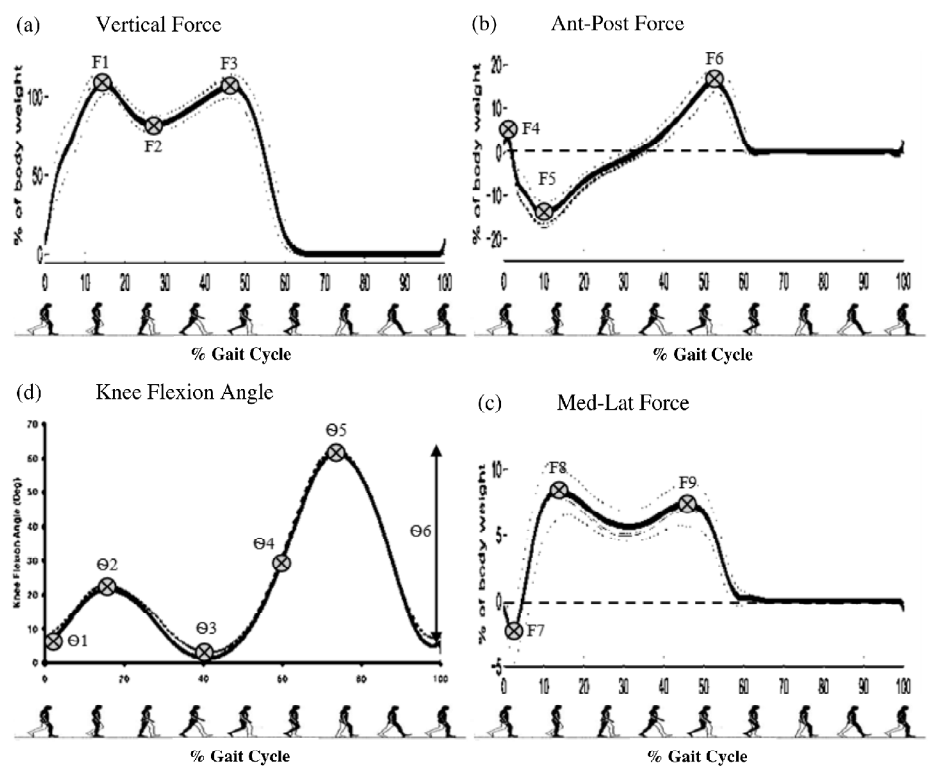


Figure 5: Modified lower extremity model introduced by Eltoukhy and Asfour (2009)

Ground reaction forces and knee joint angular kinematics are the typical main gait variables that are statistically analyzed. In this research it was decided to go beyond that and to study the events that occur within each variable individually. This in-depth analysis of the gait variables enables us to have a more accurate judgment of the model performance. The subset of variables selected was based on the work done by Benedetti *et al.* (2000). These variables were then used in the statistical analysis. Figure 6 shows the ground

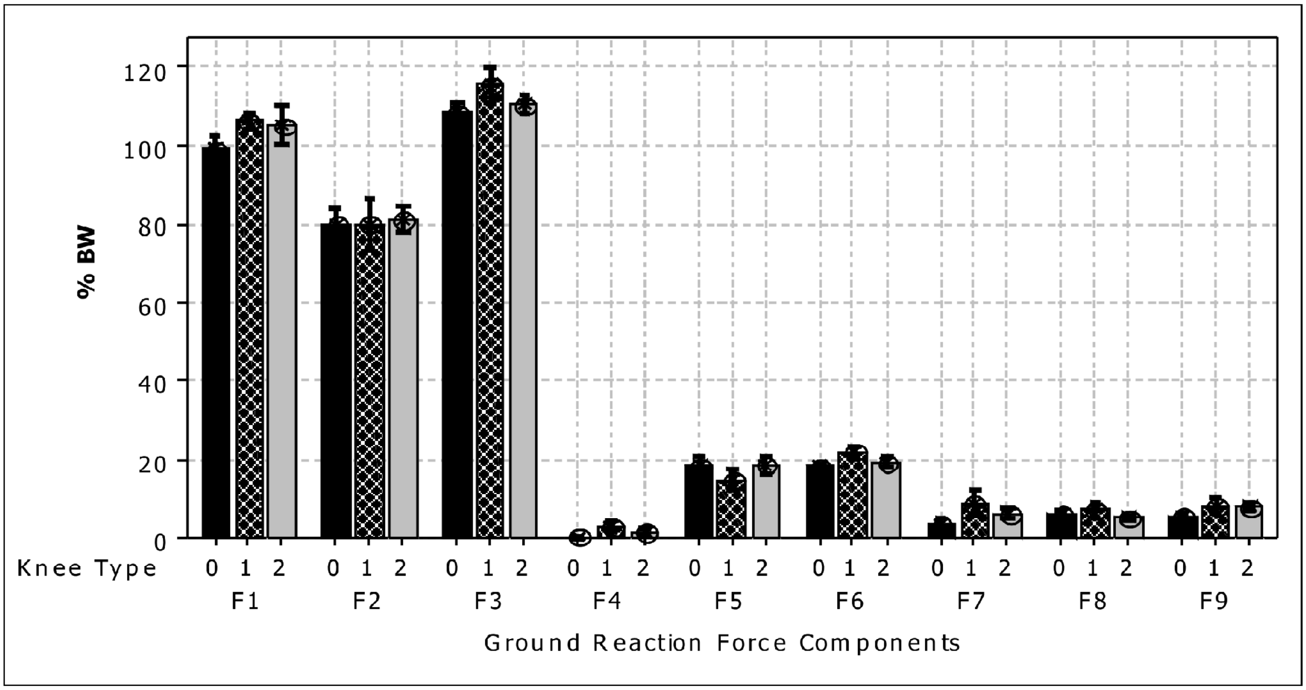


F1:Maximum vertical loading response	F6:Maximum Fore-Aft terminal stance	Θ2:Maximum Flexion loading response
F2:Maximum vertical midstance	F7:Maximum Med-Lat loading response	Θ3:Maximum Extension stance
F3:Maximum vertical terminal stance	F8:Maximum Med-Latmidstance	Θ4:Flexion toe-off
F4:Maximum Fore-Aft loading response	F9 :Maximum Med-Lat terminal stance	Θ5:Maximum Flexion swing
F5:Maximum Fore-Aft midstance	r1:Flexion heel-strike	Θ6:Total sagittal plane excursion

Figure 6: The gait parameters measured.

reaction forces in the X, Y, and Z directions as well as the knee flexion angle measured during the gait session. The figure also depicts the specific force and angle values at the different point of times during the gait cycle that were statistically analyzed.

As shown in the figure, three main points (F1, F2, and F3) in the vertical force component (Figure 6-a); also, F4, F5, and F6 were recorded from the Ant-Post force component (Figure 6-b). The last three force components recorded were the F7, F8, and F9 and that is from the Med-Lat force plot (Figure 6-c). Six angle values were recorded from the knee flexion angle component. These angle components were Θ1 to Θ6 (Figure 6-d).



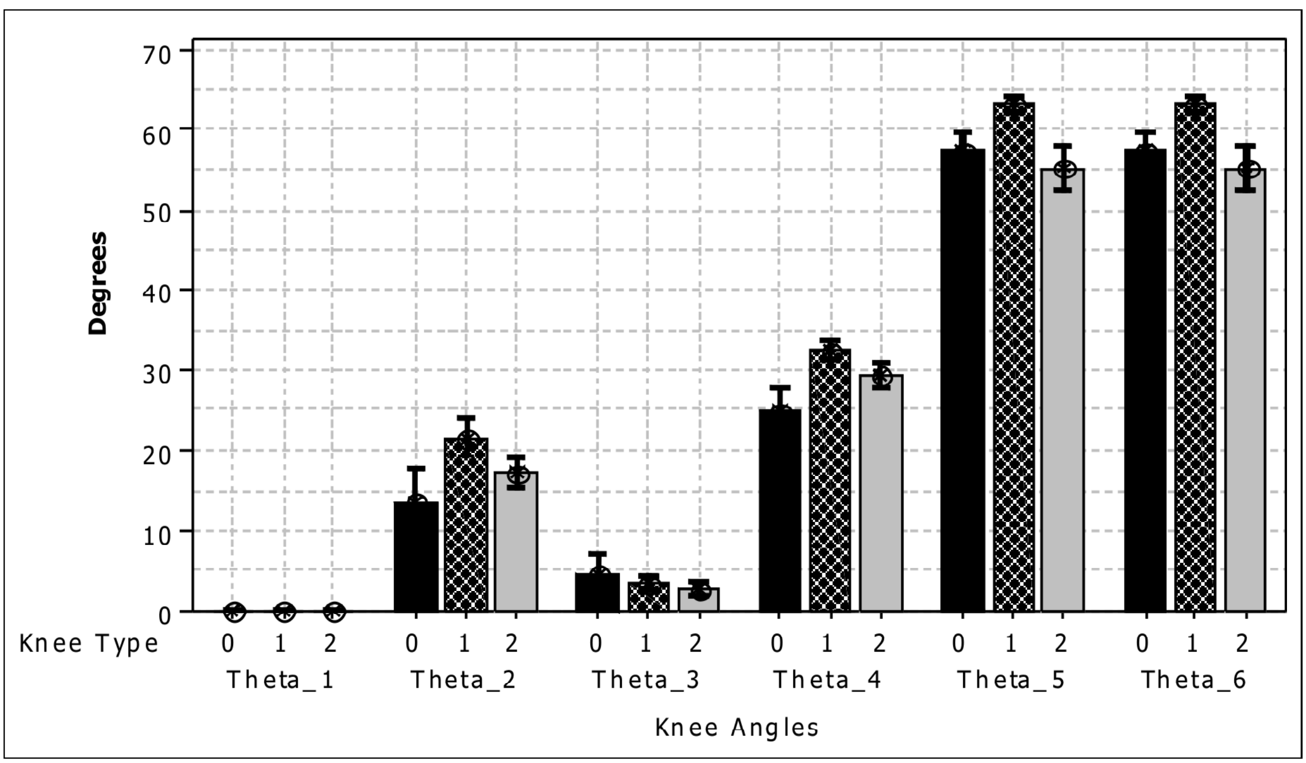


Figure 7: Interval plots of (a) the ground reaction forces (F1 to F9) and (b) the knee flexion angle (Θ1 to Θ6) for all three groups, Control "0", Metallic "1", and Allograft "2"

3. RESULTS AND DISCUSSION

The data collected from the two patient groups (metallic and allograft knee joints) was plotted along with the control group (normal knee joint). Figure 7 depicts two interval plots for both the ground reaction forces as well as the knee flexion angle measured.

As shown in figure 7, each of the force and angle components was plotted in the form of the mean and standard deviation values for all three groups, control, metallic, and allograft. For the vertical ground reaction force (Z direction) components, both the metallic and allograft groups showed higher average forces when compared to the control group,for the maximum vertical loading response, F1, and the maximum vertical terminal stance, F3 while they showed almost an equal magnitude for the maximum vertical midstance, F2.

The Ant-Post force values (F4-F6) resulted in a similar pattern as the vertical forces where the metallic and allograft groups showed higher values when compared to the control group for both F4 and F6, yet, in case of the maximum Fore-Aft midstance force, F5, the metallic group resulted in lower magnitude while the allograft group resulted in higher forces when compared to the control group. Similar pattern was also obtained in case of the Med-Lat force values, only the F8, maximum Med-Latmidstance, showed higher forces for the metallic group and similarmean value for allograft group when compared to the control group.

In regard to the flexion knee angle values, the following conclusions can be drawn. In general, the metallic group showed higher knee flexion angle values (r2: Maximum Flexion loading response, r3: Maximum Extension stance, r4: Flexion toe-off, r5: Maximum Flexion swing, and r6: Total sagittal plane excursion) as compared to the allograft group, in other words, the allograft group showed stiff-knee gait pattern.Note that only in case of the r3 (maximum extension stance), the control group showed higher mean value than the metallic and allograft groups which can be explained because of the range of motion loss resulted from the surgery when compared to the control group.

4. STATISTICAL ANALYSIS

A statistical analysis of the gait data collected was performed as follows; two Multi-Analysis of Variance (MANOVA)were conducted for both the ground reaction force components as well as the knee joint angle. The factor tested was the knee type (Normal, Metallic, and Allograft), on the other hand the variables tested were the different force components of the three ground reaction forces in the X,Y, and Z directions (F1 to F9) as well as the knee angles (r2 to r6). The data was first tested for normality. The basic data descriptive statistics as well as the MANOVA results are summarized in table 2, 3, and 4 respectively.

Table 2
Ground Reaction Forces and Knee Angles Descriptive Statistics

Variable	*Mean ± StDev*	*Variable*	*Mean ± StDev*
F1	103.7 ± 5.6	r**1**	0.0
F2	80.3 ± 6.6	r**2**	17.5 ± 5.1
F3	111.5 ± 5.4	r**3**	3.6 ± 2.1
F4	1.6 ± 1.6	r**4**	28.9 ± 4.3
F5	17.2 ± 3.5	r**5**	58.5 ± 4.6
F6	19.8 ± 2.4	r**6**	58.5 ± 4.6
F7	6.1 ± 3.6		
F8	6.0 ± 1.9		
F9	7.0 ± 2.3		

Table 3
MANOVA for Knee Replacement Type
(Ground Reaction Forces)

			DF		
Criterion	*Test Statistic*	*F*	*Num*	*Denom*	*P*
Wilks'	0.04444	7.903	18	38	**0.000**
Lawley-Hotelling	7.87640	7.876	18	36	**0.000**
Pillai's	1.56107	7.904	18	40	**0.000**
Roy's	5.31098				

s = 2 m = 3.0 n = 8.5

Table 4
MANOVA for Knee Replacement Type (Knee Angles)

			DF		
Criterion	*Test Statistic*	*F*	*Num*	*Denom*	*P*
Wilks'	0.05324	20.003	8	48	**0.000**
Lawley-Hotelling	9.14198	26.283	8	46	**0.000**
Pillai's	1.40680	14.822	8	50	**0.000**
Roy's	8.07144				

s = 2 m = 0.5 n = 11.0

As shown in the MANOVA tables and based on the Wilks criteria, the data suggests that the type of knee replacement is associated with changes in gait pattern.As tables 4 and 5 indicate, other similar tests, namelyPillai's Trace, Hotelling's Trace, and Roy's Largest Root test, also lead to the same conclusion. The Wilks' lambda test is used to measurethe overall significance of the model. When the overall model is significant, then the significance of the individual variables can be persued. After statistically significant evidence was obtained from the MANOVA tests, the individual ANOVA analyses for both the ground reaction forces (GRF) and knee flexion angles were performed and the results were summarized in table 5.

Table 5
Descriptive Statistics and ANOVA Results

Variable	*P Value**	*Control Group*	*Metallic Group*	*Allograft Group*	*P Value (Post-hoc analysis)* Control Group Vs. Metallic Group	Control Group Vs. Allograft Group	Metallic Group Vs. Allograft Group
GRF		Mean±Std	Mean±Std	Mean±Std			
F1	0.010	99.5±4.2	106.3±3.0	105.2±6.8	**Sig.**	NS	NS
F2	NS	79.8±5.6	79.8±9.2	81.2±4.6	NS	NS	NS
F3	0.006	108.5±3.3	115.6±6.6	110.4±3.2	**Sig.**	NS	**Sig.**
F4	0.001	0.2±0.07	2.7±1.8	1.7±1.3	**Sig.**	**Sig.**	NS
F5	0.028	18.3±3.3	14.8±3.3	18.4±2.9	**Sig.**	NS	**Sig.**
F6	0.001	18.2±1.1	21.9±2.5	19.3±1.8	**Sig.**	NS	NS
F7	0.004	3.6±1.7	8.7±4.6	6.0±1.9	**Sig.**	NS	NS
F8	NS	6.2±1.1	6.9±2.7	5.0±0.9	NS	NS	NS
F9	0.007	5.3±1.0	8.0±2.9	7.8±1.3	**Sig.**	**Sig.**	**Sig.**
Knee angles							
r**2**	0.001	13.6±5.6	21.6±3.2	17.2±2.7	**Sig.**	NS	NS
r**3**	NS	4.6±3.1	3.4±1.3	2.7±1.3	NS	NS	NS
r**4**	0.000	24.7±4.3	32.5±1.8	29.5±2.1	**Sig.**	**Sig.**	NS
r**5**	0.000	57.3±3.2	63.2±1.5	55.1±4.0	**Sig.**	NS	**Sig.**
r**6**	0.000	57.3±3.2	63.2±1.5	55.1±4.0	**Sig.**	NS	**Sig.**

* According to analysis of variance unless otherwise indicated. Sig.: significant NS: not significant

Table 5 basically shows the results of the individual ANOVA tests for all GRF components and knee flexion angles. The table also shows the P values, as well as the mean and standard deviations for all variables and that is for each group separately. The table also summarizes the post-hoc analysis results; the post-hocperformed compared the control vs. the metallic, the control vs. the allograft, and the metallic vs. the allograft groups.

In general, the allograft showed similar values for both the forces and angles during gait when compared to the control group. In other words, no statistically significant differences were found between the two groups, that is for all force values (except for F4 and F9) and knee angles (except forr4). On the other hand, the metallic group showed statisitcal differences in most of the force values (except fpr F8) and knee angles (except for r3) when compared to the control group.

Finally, to exclude the age factor as a possible reason behind the finding that the allograft group resulted in less gait deviations compared to the metallic group in comparison to the control group, the following statistical analysis was conducted. First a separate MANOVA analysis was conducted with the "Age" set as the factor been modeled and the variable set were the flexion knee angles (r2 to r5) as shown in table 6.

Table 6
MANOVA for Patients' Age (Knee Angles)

Criterion	*Test Statistic*	*F*	*DF* *Num*	*Denom*	*P*
Wilks'	0.00016	1.499	56	9	**0.265**
Lawley-Hotelling	75.73244	0.676	56	2	**0.763**
Pillai's	3.16755	1.359	56	20	**0.227**
Roy's	61.09191				

s = 4 m = 4.5 n = 0.0

As shown in the table and based on the three MANOVA indices, there was a clear evidence that no statistically significant effect of the patients' age on the knee kinematics. The second analysis performed was a set of three MANOVA tests of the ground reaction force components (F1 to F9) with the "Age" set as the factor tested. The following table summarizes the MANOVA outputs for these three tests.

In was also evident that in case of the kinetics, the patients' age had failed to show any statistically significant effect on the ground reaction force components produced during gait.

Table 7
MANOVA for Patients' Age (Ground Reaction Forces)

Vertical Forces (F1-F3)			*DF*		
Criterion	*Test Statistic*	*F*	*Num*	*Denom*	*P*
Wilks'	0.00209	1.613	42	9	**0.227**
Lawley-Hotelling	24.80947	0.985	42	5	**0.579**
Pillai's	2.53192	1.932	42	15	**0.084**
Roy's	13.96643				
Fore-Aft Forces (F4-F6)			*DF*		
Criterion	*Test Statistic*	*F*	*Num*	*Denom*	*P*
Wilks'	0.00266	1.467	42	9	**0.279**
Lawley-Hotelling	29.76959	1.181	42	5	**0.475**
Pillai's	2.39169	1.404	42	15	**0.242**
Roy's	22.86074				
Med-LatForces (F7-F9)			*DF*		
Criterion	*Test Statistic*	*F*	*Num*	*Denom*	*P*
Wilks'	0.00625	20.003	42	9	**0.513**
Lawley-Hotelling	16.62683	0.660	42	5	**0.794**
Pillai's	2.33854	1.263	42	15	**0.321**
Roy's	10.82468				

5. CONCLUSIONS

A three-dimensional (3D) musculoskeletal model of the lower extremity introduced by Eltoukhy andAsfour (2010) has been utilized in the joint replacement applications. The objective of this paper was to test the applicability of the introduced model in situations that involves joint replacement and to show that the model can be used for such applications such as surgery planning. The case study of the research work presented in this paper involved the comparison of the gait pattern between two main knee joint types, Metallic and Allograft knee joints against normal subjects (Control group). A total of fifteen subjects participated in this study, five subjects in each group. Based on the results obtained from the MANOVA tests, the allograft group had less significant gait deviations than did those in the metallic group.In particular, the metallic group patients had greater gait deviations both in the loading-response phase, and in the Fore-Aft terminal stance phase.

In conclusion, our findings suggest that implantationof hinged total knee prosthesis with removal of one or two of thequadriceps muscles provide good functional resultsduring gait. Additional studies should be performedto evaluate the relationship between the numberand extent of the quadriceps' heads excised andboth the knee mechanics during gait and the long-termsurvival of the prosthesis.It was also concluded that based on the study conducted and the statistical evidence obtained that the introduced model can be used for applications that involves joint surgeries such as knee replacement that ultimately can be utilized in surgery planning.

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