ISSN: ISSN: 0974-5823 Vol. 7 No. 2 February, 2022

International Journal of Mechanical Engineering

Empirical and simulated investigation of Bio-ceramic Cordierite as hip joint implant using hip simulator device

Mohammad Hasan Basheet[a,], Fadhil Kareem Farhan[b], Abdulrahman N. Abed[c]

[a]*Biomedical Engineering Department, Engineering College, Al-Nahrain University, Jadriah, Baghdad, Iraq*

[b]*Department of Medical Physics, College of Science, The University of Karkh for Science.*
[c]*Mechanical Engineering Department., Engineering College, Al-Nahrain University, Baghdad, Iraq*

Abstract

The use of bio ceramics in prosthetic joints is discussed in the presented work. Chemical coprecipitation was used to make cordierite powders, which were mixed with a water-based sol–gel containing MgO, SiO_2, and Al_2O_3. With varying weight percentages of Al_2O_3, Mgo, and SiO_2 powders, a total of 5 specimens were created. The acetabular cup and hip ball joint were formed with the use of slip casting approach, and moments and forces were measured throughout walking with the use of AMTI force 5 hip simulator based on curves regarding the angular motion angles of the hip joint in 3 axes (flexion\extension, adduction\abduction, and internal\external rotations), while force which is applied (vertically) on hip joint throughout one gait cycle in accordance with the ISO standard (14242_1\ 2014). Throughout gate cycle, descriptive data for the resultant moment and force were examined.

Keywords: Cordierite; AMTI Force-5 hip simulator; slip casting; forces and moment.

1. introduction

Throughout the past 10 years, ceramic materials have gained popularity as dental and medical implant materials. Hundreds of different ceramic compositions were examined for biocompatibility and proven to be appropriate to be used as surgical implant construction materials [1]. Generally, bio ceramics are classified into one of three groups: semi-inert (bio-active), like (glasses/glass ceramics and calcium phosphate), bio-resorbable, like (porous bio-active and new advanced ceramics), and inert (non-resorbable), like (silica, alumina, zirconia) [2][3]. Recently, implants like artificial hip joint (AHJ) had shown to be exceptionally reliable according to technical requirements. AHJs had reached a point where, at least for certain designs, failure rates of < 5% over a decade might be projected, thanks to considerable development and research over two decades period. [4] Joint simulator tests were created to mimic the bio-mechanics of human joints in controlled environment. Simulator testing results could prove a material's performance for a certain geometrical design under a number of operating conditions. The simulator provides rotations about three axes in sagittal plane, abduction/adduction plane, and about vertical (i.e. femoral) axis, as well as loading profiles that replicate stair climbing or walking, among other activities. Since 2000, ISO has developed an international approach for obtaining comparable results between laboratories. [5] Bones are subjected to a stress of about 4MPa throughout regular activities, but ligaments and tendons are subjected to peak stresses of 40MPa–80MPa. The average load on a hip joint is up to three times the body weight (3000N), with a peak load of 10 times body weight throughout jumping. Those stressors are also repeated and fluctuate based on activities including sitting, standing, stretching, jogging, and climbing. [6]

Various researchers are looking into hip contact forces throughout day-to-day activities. A Comparison of in-vivo measured loads in hip, knee, and spinal implants throughout level walking summarizes the partially published load data that has been acquired in earlier in-vivo measurement researches on 10 patients who have hip endoprostheses, 9 patients with telemeterized knee endoprostheses, and 5 patients who have the vertebral body replacements [7]. The resultant intersegmental loads for the hip joint are commonly characterized with regard to 3 mutually perpendicular force components and the 3 corresponding moments about reference axis, which was introduced in 1985[8][9].

Instrumented implants were used for measuring gait patterns and hip contact forces throughout routine activities, and synchronous analyses of ground reaction forces and gait patterns were done in 4 patients throughout the most common daily living activities. The study is focused upon the loading of femoral implant component, yet complete data is also stored on associated compact disc. It includes data on gait and hip contact force, along with computed muscle activity during stair climbing and walking and the frequency of daily activities identified in hip patients. The hip joint and proximal femur's mechanical loads and function are so fully documented [10].

The hip joint loading throughout different skiing activities was studied, while the results were compared to running and walking. The findings are important in determining which skiing activities are appropriate for people who have had a total hip replacement. [11] Using instrumented hip implants, the contact forces in joints have been evaluated in 10 participants throughout 9 of the most physically demanding and frequent daily life activities. From the inter- and intra-individually widely varied individual data, typical amounts and directions of high and average joint loads have been derived. Those data might as well be utilized to investigate bone remodeling at the interface of implant-bone, assess tissue straining in finite element investigations, and verify analytical loading predictions, amongst other things [12].

.

2. Materials and Methods

2.1 Raw material and preparation process

The bioceramic cordierite has been synthesized utilizing the coprecipitation process with the use of high purity powders of MgO, Al_2O_3, and SiO_2 in the stoichiometric ratio of cordierite. Three white powders, including Al_2O_3 from (Riedel-de Haen, Germany), MgO (Parchem Fine and Specialty Chemicals, U.S.) with a 99% purity, and SiO_2 from (Daejung Chemicals), were utilized to synthesize ceramics cordierite samples. Boric acid was utilized as a nucleation agent, and five distinct groups were formed based on the computed chemical composition and molecular weight fraction for every one of the groups (xAl_2O_3, xMgo, and $xSiO_2$), as can be seen from Table1.

Table 1

chemical composition of prepared powder samples

sample	mole fraction	system	MgO wt%	Al_2O_3 wt%	Sio_2 wt%	molar mass(g/mol)
S1	(1:1:1)	$MgAl_2SiO_6$	20%	50%	30%	202.344
S2	(1:2:1)	$MgAl_4SiO_9$	13%	67%	20%	304.304
S3	(1:1:2)	$MgAl_2Si_2O_8$	15%	39%	46%	262.424
S4	(2:1:2)	$Mg_2Al_2Si_2O_9$	27%	34%	40%	302.728
S5	(2:2:5)	$Mg_2Al_4Si_5O_{18}$	14%	35%	51%	584.928

2.2 Specimen's preparation by using slip casting method

Five samples from each system including hip cup and ball was made according to slip casting method, Slip casting is one of ceramic forming process and it is considered the most traditional method for producing varied pieces which may be of complex forms. Because of irregularity of hip joint, this method was used and this is done by following steps:

1. in Mold-Making Process, white cement was used to produce the mold, this cement is a well-mixed with water before the casting process, the hip ball was placed in container, then we start the gradual casting process, casting was carried out in two stages for the purpose of making half a mold, the mold remaining for 1 hour to become stronger then the ball was removed and final shape of mold was exposed to incubation with temperature of 100 C^o,, the same procedure as mentioned above was repeated to produce the acetabular cup of hip joint.
2. The following step include that the powder of ceramic from each system will mixed with distilled water for half hour until making the mixture is liquid and easily pourable.
3. the mixture will slowly pour into the mold to the point where it reaches the very top. This mold is left full for about 5 min., this allowing the cup's outer part to harden and thicken and it will notice the slip sink into the mold, The capillary migration of liquid into the mold pores leads to forming a consolidated layer of particles on the surface of the mold, then pour the rest of the casting slip back into the mixture, next, pour in mold again to ensure that the cup is fully formed, then the ball of hip joint placed in the center of cup layer in order to made a fitting layer, same procedure will performed in case of forming.
4. the casted shape will have released from the mold once it is dried, and incubated with 100 C^o, smooth out any creases or imperfections using silicon carbide with grade (P1000).
5. the hip ball the final process includes firing the specimens by exposed to sintering temperature with 1250 C^o, this done using The CARBOLITE SWF furnace. Now specimens as shown in fig.1 will ready to evaluated in AMTI's Force-5 hip simulator.

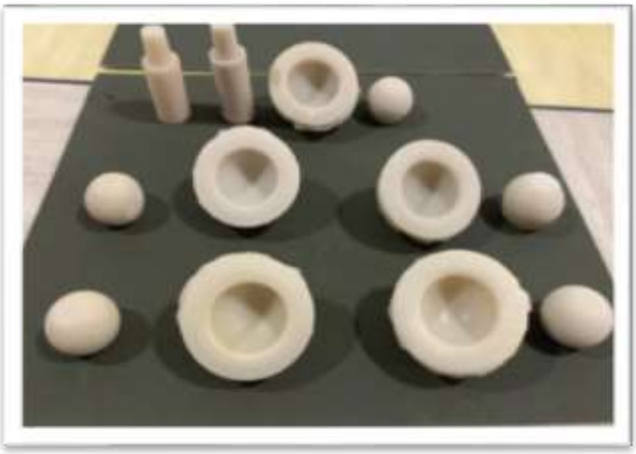


Fig. 1: final acetabular cup and hip ball

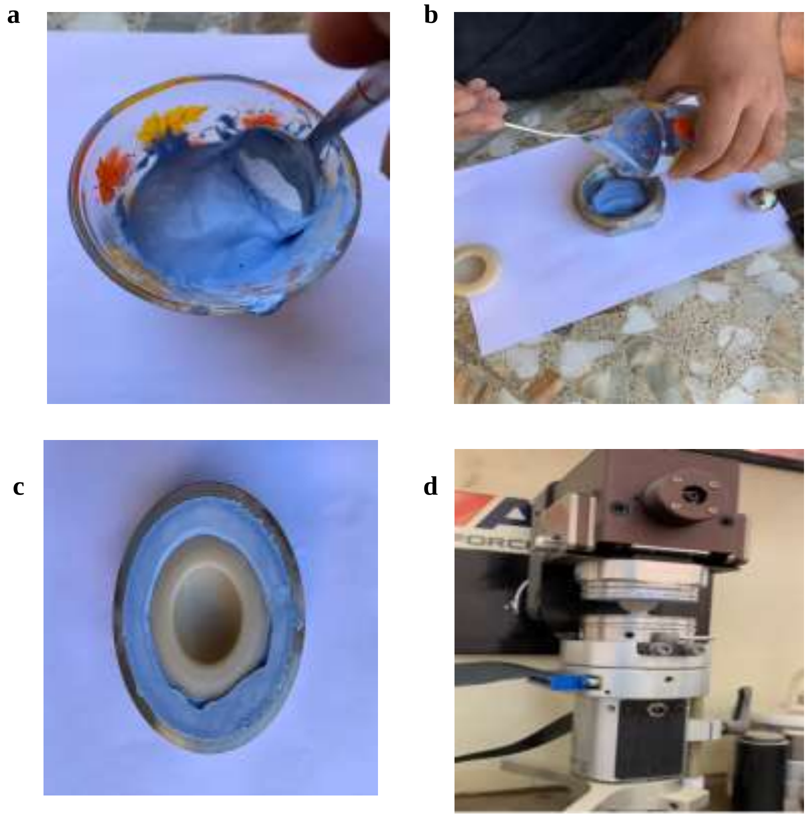


Fig. 2: a) medical cement in mixing cup; b) implant in upper holder; c) implant are ready for testing; d) specimen with holders placed in simulator machine

the method of installing implant specimens on the machine. All of the components needed for the installation include the femoral ball mounted on the lower specimen holder, the upper specimen (acetabular cup) holder, cup implant, cement and mixing cup. First step to installation include that medical cement is mixed and poured into the upper specimen holder as shown in Fig. 2 (a), small amount of cement will have added and the implant is placed approximately in the centre of the specimen holder as shown in Fig.2 (b), furthmore, the rest of cement added more and to insure that the implant and cement will inclined with same edge of upper holder, now, implant are ready for testing as shown in Fig. 2 (c).after 2 hours the cement dried, acetabular cups mounted to the upper specimen holders and femoral components (ball) installed on the lower specimen holders, then placed on the one the specimen holder in Force 5 machine as shown in Fig.2 (d).

2.3 *Input signals for AMTI-Force 5*

In order to examine the components of the joint that were manufactured by the sliding casting process in the AMTI-force 5, the device is programmed by entering data according to ISO standards, where signal was entered, including the process of walking,, which include the angles of angular displacement of hip joint in 3 axes (flexion\extension, abduction\abduction, and internal\external rotations) and force which is applied on hip joint both are during an entire gait cycle, Fig. 3 (a) represent main display screen for the NetControl software, for walking process, the input signal was according to (14242_1\ 2014) ISO standard as shown in Fig. (b), the input signal and data entry was according to Orthload database which is manly depend on the study by G. Bergmann and et al, 2001 [10].

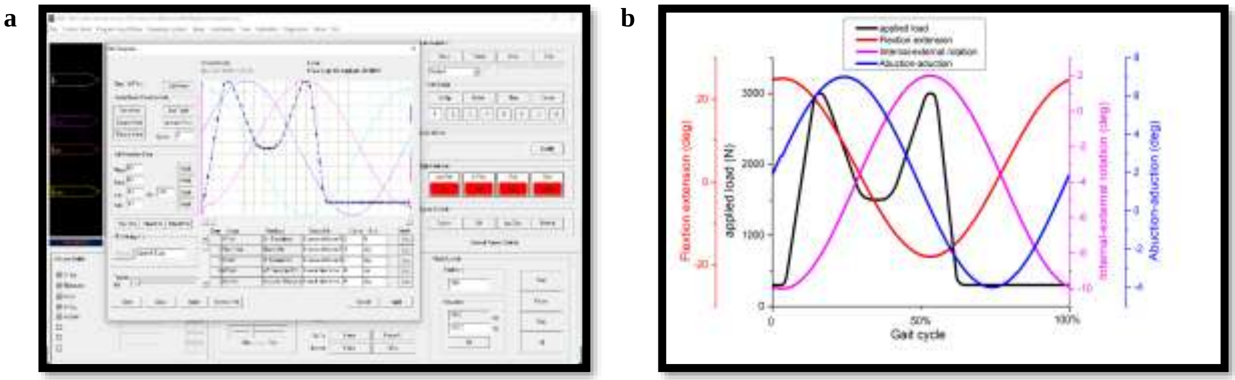
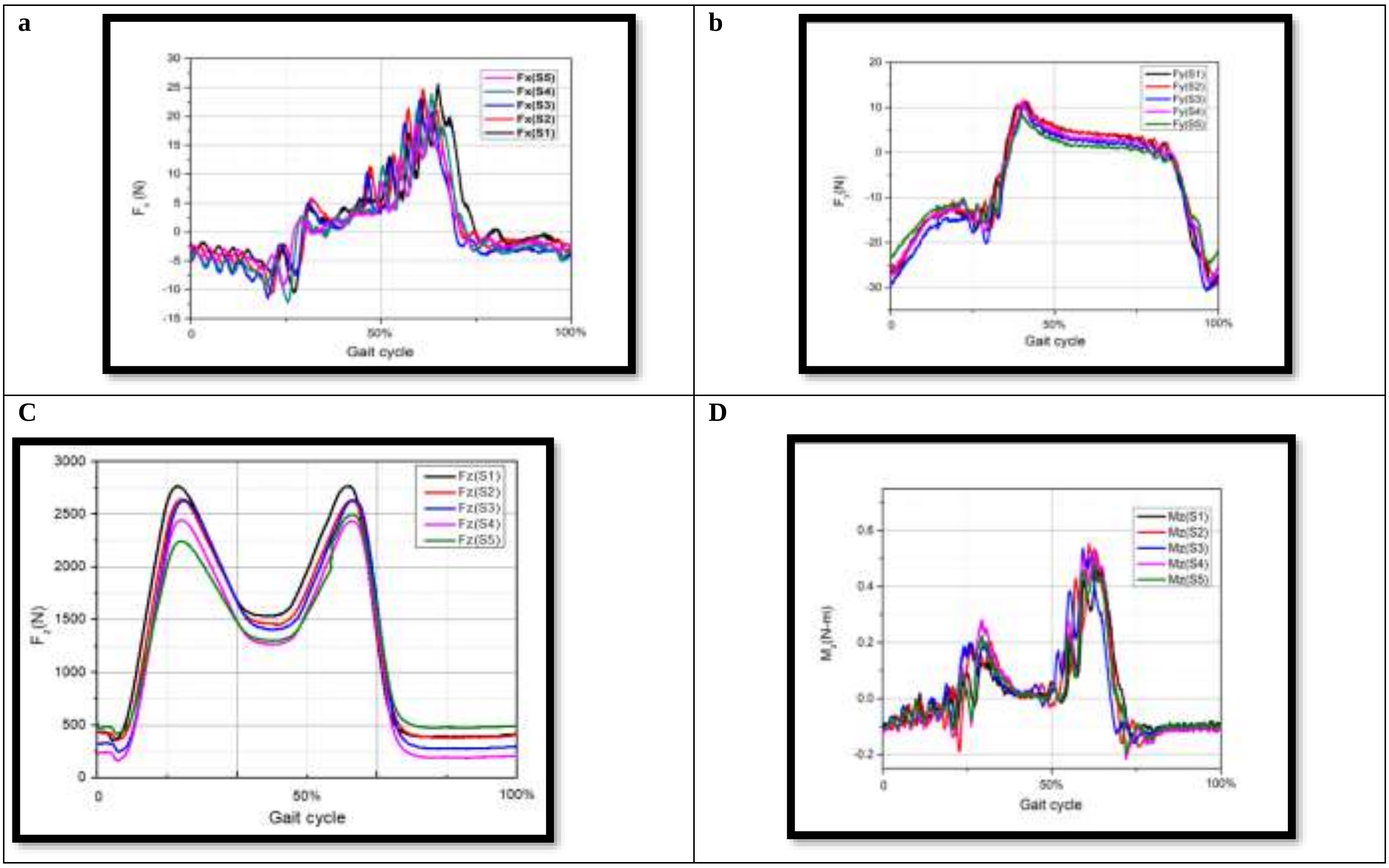


Fig. 3: (a)The Main Display Screen along with one of the available control panels provides the primary user interface to control the simulator machine; (b) input waveform signal according to (14242_1\ 2014) ISO standard

3. Result and Discussion

3.1. Forces and moments in (x,y,z) direction

The next curves were obtained by testing hip joint implants for the 5 systems using the walking input force and angles. Throughout one walking gait cycle, the curves indicate the moments and stresses at the joint in 3 directions. The forces are represented by Fig.4(a)–Fig.4(c), and the moments are represented by Fig. 4(d)–Fig. 4(f).



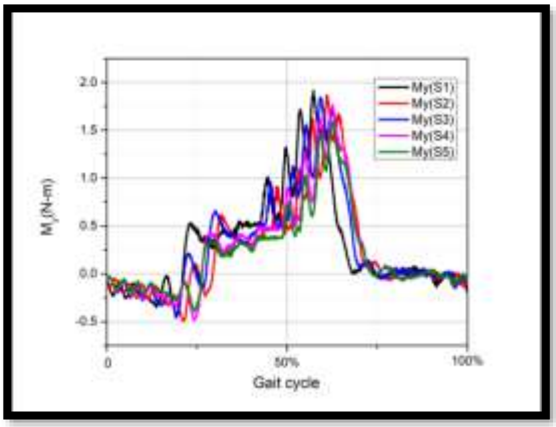
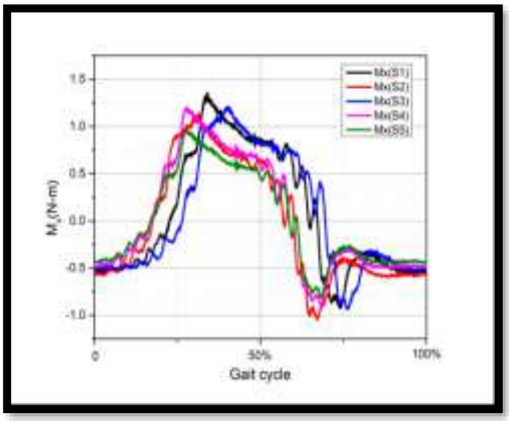
E	F
	

Fig. 4: Forces and moments at tested implants in (x, y, z)-direction throughout 1 gait cycle, (a)Fx; (b)Fy ;(c)Fz; (d)Mx; (e) My; (f) Mz.

3.2. Resultant forces (F_{res}) and resultant moments (M_{res}) in (x,y,z) direction

The resultant force for system can be shown in Fig. 5, Table 2 represent the descriptive statics for the samples and show maximum and minimum and index during the gait cycle

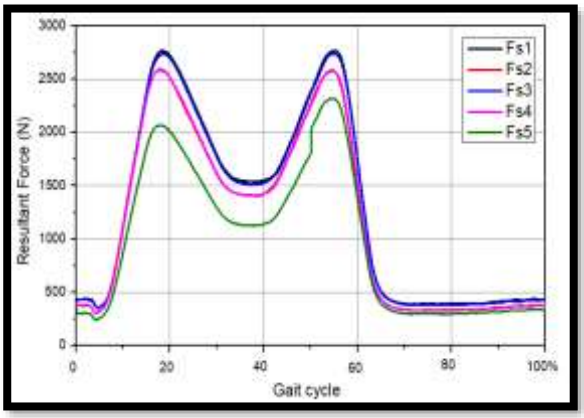


Fig. 5: Resultant force (F_{res}) of the tested samples during gait cycle.

Table 2

minimum and maximum values with index for resultant force during gait cycle

sample	N total	Mean	Standard Deviation	Minimum	Index of Minimum	Median	Maximum	Index of Maximum	Range (Maximum - Minimum)
Fs1	1000	1291.277	880.85905	350.23828	4.6%	1385.166	2767.44507	55.4%	2417.20679
Fs2	1000	1186.366	831.94418	305.64264	4.2%	1280.118	2592.32723	18%	2286.68459
Fs3	1000	1275.605	872.53535	350.98496	4.5%	1369.341	2739.07514	18.4%	2388.09017
Fs4	1000	1185.587	831.84233	302.29647	4.2%	1289.47	2584.15517	18.2%	2281.85871
Fs5	1000	987.9727	687.62866	241.83063	4.2%	1076.939	2319.29742	54.7%	2077.46679

The resultant moments for systems can be shown in Fig. 6, Table 3 represent the descriptive statics for the samples and show maximum and minimum and index during the gait cycle for walking process

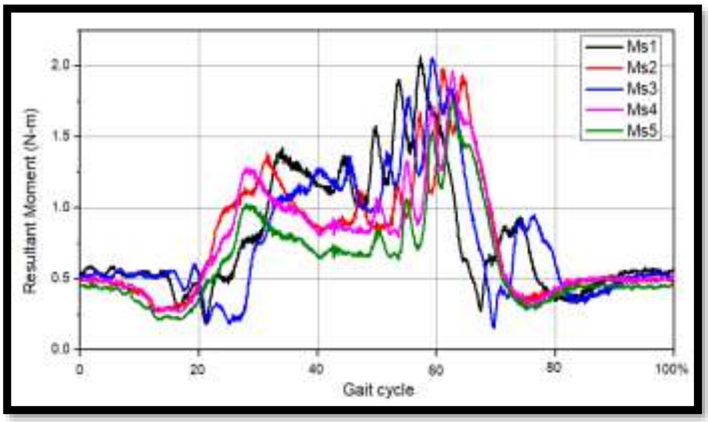


Fig. 6: Resultant Moment (M_{res}) of the tested samples during gait cycle

Table 3

sample	N total	Mean	Standard Deviation	Minimum	Index of Minimum	Median	Maximum	Index of Maximum	Range (Maximum - Minimum)
Ms1	1000	0.8035	0.42202	0.18272	21.1%	0.5697	2.0659	57.3%	1.88318
Ms2	1000	0.77536	0.40296	0.26482	12.3%	0.59098	1.97807	60.9%	1.71325
Ms3	1000	0.77871	0.42686	0.15477	69.7%	0.55382	2.0559	59.3%	1.90113
Ms4	1000	0.74594	0.3786	0.26246	13.1%	0.56436	1.96573	62.7%	1.70327
Ms5	1000	0.63141	0.32599	0.20997	13.1%	0.47339	1.76916	62.7%	1.55919

minimum and maximum values with index for resultant Moment

for Fig. 4(a) the range of forces around 36 N, the maximum value was (25.539 N) for the sample S1 while the minimum value was (-12.484 N) for S4, Fx was nearly positive throughout the activity of walking while Fy was nearly negative throughout the whole cycle as shown in Fig. 4(b), the dominant force component is the vertical component (Fz) and it much higher comparing with Fx and Fy as shown in Fig. 4(c).

Fig. 4(c) depicts the directions related to hip joint force as seen in terms of the proximal femur, and it appears like (M-shape). The 1st and 2nd maxima in the curve of load variations with time are indicated by the two arrows. The backward and forward component of stress on femoral head, which should unavoidably result in a twisting load action that is transferred between any surgical implant and the shaft of the femur throughout heel strike and toe off during the stance phase. The first peak for the samples was between (2766N) and (2242N) occurred at 21% of gait cycle, the bottom range of M-shape (1534N-1266N) at 42% of gait cycle while second peak range (2766.89N-2437N) at 63% of gait cycle. Fig.4(d) show The Moments at tested samples in the x-direction throughout 1 gait cycle with maximum value (1.33N-m) for S1 and minimum value (-1.04 N-m) for S2. The general behavior of curves for forces and moment agreement with [9][10][12][13],the wear and friction for all specimens were evaluated by using AMTI Orth-POD machine [14].

4. Conclusion

- In the previous section, the moments and stresses applied at the implant of the hip joint throughout one walking gait cycle have been shown. The implants evaluated the 3 components of the contact force F_y, F_x, and F_z in Newton and the 3 moment components M_y, M_x, and M_z in Nm. Only five hip implants were evaluated.
- Friction in the joint causes the moments, which act in addition to forces. The vector sums of the components were used to determine the resultant force F_{res} and the corresponding moment of friction M_{res}.
- The magnitude of F_{res} throughout walking varied amongst implants, yet the overall shape of the time courses was relatively similar. F_{res} exhibited a double-peak pattern in the case when walking. The results were subjected to statistical analysis.
- There have been differences in results between the implants, in which the acetabular cups and hip ball were made of Al_2O_3, MgO, and SiO_2 with the use of slip casting approach, but the moments and forces applied to them were all in the same range; therefore, all implants have the same design features in terms of moments and forces.

Acknowledgements

Great thankful to Biomedical Engineering department in Al-Nahrain University for providing support and facilities to carry out this research work.

References

[1] Hulbert SF, Hench LL, Forbers D, Bowman LS. History of bioceramics. Ceramics international. 1982 Oct 1;8(4):131-40.

[2] Mallick KK, Winnett J. 3D bioceramic foams for bone tissue engineering. InBone Substitute Biomaterials 2014 Jan 1 (pp. 118-141). Woodhead Publishing.

[3] Poitout DG, editor. Biomechanics and biomaterials in orthopedics.

[4] Marsh AC, Chamorro NP, Chatzistavrou X. Long-term performance and failure of orthopedic devices. InBone Repair Biomaterials 2019 Jan 1 (pp. 379-410). Woodhead Publishing.

[5] Affatato S, Leardini W, Zavalloni M. Hip joint simulators: state of the art. Bioceramics and Alternative Bearings in Joint Arthroplasty. 2006:171-80.

[6] Daculsi G. History of Development and Use of the Bioceramics and Biocomposites. Handbook of bioceramics and biocomposites. 2016:1-386.

[7] Damm P, Kutzner I, Bergmann G, Rohlmann A, Schmidt H. Comparison of in vivo measured loads in knee, hip and spinal implants during level walking. Journal of Biomechanics. 2017 Jan 25;51:128-32.

[8] Rydell NW. Forces acting on the femoral head-prosthesis: a study on strain gauge supplied prostheses in living persons. Acta Orthopaedica Scandinavica. 1966 May 1;37(sup88):1-32.

[9] Andriacchi TP, Strickland AB, Berme N, Engin AE, Da Silva KC. Biomechanics of normal and pathological human articulating joints. InProceedings of the NATO Advanced Study Institute 1985 (Vol. 93, p. 83).

[10] Bergmann G, Deuretzbacher G, Heller M, Graichen F, Rohlmann A, Strauss J, Duda GN. Hip contact forces and gait patterns from routine activities. Journal of biomechanics. 2001 Jul 1;34(7):859-71.

[11] van den Bogert AJ, Read L, Nigg BM. An analysis of hip joint loading during walking, running, and skiing. Medicine and science in sports and exercise. 1999 Jan 1;31(1):131-42.

[12] Bergmann G, Bender A, Dymke J, Duda G, Damm P. Standardized loads acting in hip implants. PloS one. 2016 May 19;11(5):e0155612.

[13] Bergmann G, Graichen F, Rohlmann A, Bender A, Heinlein B, Duda GN, Heller MO, Morlock MM. Realistic loads for testing hip implants. Bio-medical materials and engineering. 2010 Jan 1;20(2):65-75.

[14] Basheet MH, Farhan FK, Abed AN. Wear and friction analysis of bio-ceramic cordierite system as orthopedic material. Materials Today: Proceedings. 2022 Jan 13.