International Review of Mechanical Engineering (I.RE.M.E.), Vol. 13, N. 1
ISSN 1970 - 8734 January 2019

A Wear Formulation of Total Hip Prosthesis for Salat Activity

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Abstract – *The wear on the acetabular liner surface of total hip prosthesis due to human activity cannot be avoided. Salat is an obligation religious activity for Muslims performed five times daily, without exception for patients who used the total hip prosthesis. Salat consists of standing, bowing, prostrating and sitting on the leg motions. Many researchers have investigated the wear on the liner surface for daily activity but not for salat activity. This study has aimed to calculate wear on the acetabular liner surface due to salat activity. A new linear wear model has been proposed in order to estimate the linear wear or the wear depth on the acetabular liner surface. In addition, a volumetric wear model or volume loss on the acetabular liner surface has also been developed based on the new linear wear model. These wear model are used to calculate wear on the acetabular liner surface due to walking and salat activities. Results show that the linear wear due to salat activity is lower than walking activity, because of the intensity of salat activity is lower than walking. However, the combinations of both wear due to walking activity and salat activity need to be considered.* ***Copyright © 2019 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords*: Gait Cycle, Linear Wear Model, Salat Activity, Total Hip Prosthesis, Volumetric Wear*

Nomenclature

d	The distance of center point of head and cup
F	Force
h_C	Height of cup
h_H	Height of head
h_P	Penetration or linear wear
K_W	The dimensional wear coefficient
L	Sliding distance
N	Number of revolution or loading cycle
r	Contact radius
r_C	Contact radius of cup
r_H	Contact radius of head
r_s	The radius of the spherical articulating surface
R^*	The effective contact radius
R_C	Radius of cup
R_H	Radius of head
V	Wear volume or volumetric wear
V_C	Volumetric wear of cup
V_H	Volumetric wear of head
V_P	Volumetric wear of penetration
x	Distance of center point of the cup to the boundary of contact radius

I. Introduction

Islam is one of the major religions in the world. In 2010, Christianity was the world's largest religion with 2.2 billion adherents, whereas Islam was the second one with 1.6 billion followers [1]. Islam has five pillars for the followers, i.e., the testimony of faith, salat (prayer), giving zakat (support of the needy), fasting during Ramadhan and the pilgrimage (Hajj) to Makkah [2].

Salat is a particular way to worship God among Muslims implemented with activity. Salat activity is performed five times daily or in seventeen cycles (*rak^ahs*) daily, where one cycle consists of standing, bowing (*Ruku^*), straightening up (*I^tida̲l*), prostrating (*Suju̲d*) and sitting on the legs. Based on the Holy Qur'an and hadith, it is an obligatory religious daily activity for Muslims, without exception for Muslim patients who use a hip prosthesis.

Total hip arthroplasty (THA) is one of the most successful orthopedic procedures for the diseased cartilage and bone of the hip joint that replaced surgically with implant materials. The THA involves surgical removal of the diseased femoral head and socket and replacing them with the hip prosthesis. It consists of acetabular cup, acetabular liner, femoral head, and stem.

One of the main problems for the THA patient during their daily activities is dislocation [3]. The dislocations are divided into early dislocation and late dislocation [4].

The early dislocation occurs due to the impingement of the femoral neck to the rim of acetabular liner, and the late dislocation is mostly related to wear on the surface of acetabular liner [4]-[5]. The wear phenomenon on the surface liner of the total hip prosthesis due to daily activities cannot be avoided. Daily activities such as walking, fast walking, running, walking downstairs and upstairs produce load and sliding variations on the acetabular liner surface that cause wear. The applied load and the sliding in this situation are variables based on the wear model of Archard in relation to adhesive wear [6] as shown in Eq. (1). In this equation, V is the wear volume in mm^3, K_W is the dimensional wear coefficient in mm^3/Nm, F is the applied load in N, L is the sliding

https://doi.org/10.15866/ireme.v13i1.16340

distance in mm, and N is the number of sphere revolutions or the number of loading cycles.

$$\frac{V}{L} = K_W FN \quad (1)$$

The dimensional wear coefficient K_W is obtained from experimental data, whereas load and sliding distances are derived from the gait cycle. Walking gait cycle is the most widely used data by researchers in order to predict wear on the acetabular liner surface of the total hip prosthesis. Paul et al. [7] have provided load data during the walking gait cycle, whereas Calonius et al. [8] have provided sliding distance data from the walking gait cycle and a hip simulator. In order to obtain the linear wear on the acetabular liner surface, many researchers have performed experiments and they have proposed the wear calculation model analytically and numerically.

Many researchers have investigated wear on the liner surface considering walking condition, although many kind of research have performed it using the hip simulator, they have tried to approximate walking condition. Dowson et al. [9] have presented both linear and volumetric wear data from tests on Charnley hip prosthesis with hip simulator under simulated walking condition and they have proposed the linear wear calculation model. Kauzlarich et al. [10] have developed a wide range of the wear calculation model based on local Archard wear in various conditions, such as spherical ended pin or pivot, crossed cylinders, journal bearing and spherical bearing. Specifically for spherical bearing, the formula has been validated, and it has showed a good agreement with Dowson's experimental data. Wu et al. [11] have proposed computer algorithms in order to estimate the wear appearing in the total hip prosthesis by using finite element analysis based on the modified Archard wear law under walking condition.

Stanfos et al. [12] have initiated the wear research in the total hip prosthesis by using the boundary element method. Liu et al. [13] have proposed the new formula to predict wear of polyethylene in the hip prosthesis, where it is based on wear volume being dependent on and proportional to the product of the sliding distance and contact area. Liu et al. [14] have continued the research using the formula by considering the effect of motion inputs on the wear prediction of artificial hip joints, wherein this study the full simulated walking cycle condition is based on a walking measurement. Alvarez-Vera et al. [15] have investigated the wear performance in the FIME II hip joint simulator under normal gaits, where the total hip prosthesis used a metal-metal Co-Cr alloy with different boron additions. Uddin et al. [16] have proposed the prediction of wear in hard-on-hard of the hip joint prosthesis using finite element method for walking gait cycle. Uddin et al. [17] have also shown the wear measurement of the conventional crosslinked polyethylene and highly crosslinked polyethylene cups using a coordinate measuring machine (CMM). They have continued their study by presenting a wear model in order to estimate the evolution of wear in hard-on-hard bearing components under the influence of the cup abduction angle, Shankar et al. [18]. Recently, Uddin et al. [19] have showed the evaluation of hip implant wear measurements by CMM technique with uncertainty analysis. Based on the previous literature, the wear study on the liner surface of the total hip prosthesis due to salat activity has been not performed. However, the wear prediction on the liner surface due to salat activities is needed to improve the ability of hip prosthesis for Muslim patients. Therefore, this research gives the contribution to science in the field of tribology specifically the wear prediction. This study has aimed to calculate the linear and the volumetric wear on the acetabular liner surface of the total hip prosthesis due to salat activity. In this research, a new linear wear model of the total hip prosthesis proposed to reach this purpose. Besides, a new volumetric wear has also been introduced; it is the result of the development of the present linear wear model.

II. Wear Formulation of Total hip Prosthesis for Salat Activity

II.1. Salat Gait Cycle

The requirement parameters of linear and volumetric wear are load and sliding distances obtained from human activities, such as walking activity. In general, walking gait cycle consists of stance and swing stages, where Paul et al. [7] have summarized the hip joint load or hip contact force for walking activity with different speed level (Table I). Hip contact force has been based on the calculation of gait analysis data using simplified muscle models. In addition, Bergmann et al. [20] have also investigated in many hip joint cases such as investigation of friction in total hip prosthesis measured during walking, realistic loads for testing hip implants [21], hip joint contact force during stumbling [22], Hip contact forces and gait patterns from routine activities [23], loads acting at the hip joint [24], hip joint loading during walking and running, measured in two patients [25], etc.

Bergman et al. [26] have performed an investigation in a walking case based on the recording of load action through the hip joint implant. The hip contact force has been measured by in vivo with instrumented implants.

Their experiment has developed two types of instrumented hip implants with telemetric data transmission [23].

TABLE I
SUMMARY THE VALUES OF HIP JOINT LOAD
FOR SEVERAL LEVEL WALKING ACTIVITIES [7]

Level walking activity	Max. Joint force / Bodyweight
Slow	4.9
Normal	4.9
Fast	7.6

Based on the survey in many works, literature that has discussed the gait cycle of salat is difficult to be found. Hashim et al. [27] have investigated gait cycle research for salat activity based on the ground reaction force (GRF) method. This study has been performed to analyze the pattern of the salat gait cycle in comparison to the walking gait cycle. It has been concluded that salat gait cycle is similar to walking gait cycle. The salat gait cycle forms like M-shape and it is similar to the walking gait cycle form, in other words, salat activity like static walking exercise. Therefore, it can be assumed that the sliding distance value of salat gait cycle is similar to the normal walking gait cycle, i.e., $1.65r_s$. While based on the comparison of walking gait cycle [7] and [21], the maximum reaction force for salat gait cycle is higher than the normal walking one. Thus, the applied load in salat gait cycle can be approximated with fast walking one of Paul's graph [7] and Bergman's graph [21]. Based on Table I, it can be seen that the maximum of the fast walking gait cycle, i.e., 7.6 times body weight on the hip.

Recently, Jamari et al. [28] have investigated the range of motion (RoM) on hip skeleton during the salat activity by using virtual simulation. The study is the continuation of their research about finite element analysis for human activity [29] and impingement during salat [30]. The salat activities consist in standing, bowing, straightening up, and the transition of standing towards prostration, prostration, sitting between the two prostrations and sitting. The results are the RoM values in each salat activity, where this result is essential to predict the impingement occurrence on the acetabular liner due to salat activity. However, this research has no investigated load due to salat activities.

II.2. Wear Modeling

Sliding distance is one of the variables in the Archard wear model, where the hip joint case is obtained from the gait cycle produced by human activities or from the hip simulator. Table II shows the value of the sliding distance per cycle in a wide range of gait and hip simulator.

TABLE II
THE SUMMARY OF THE SLIDING DISTANCE
FOR ELEVEN SIMULATORS AND GAIT [8]

Cases	L [mm]
HUT-3 [31]	$1.71r_s$
HUT-BRM [32]	$2.46r_s$
MMED-BRM [33]	$2.46r_s$
MTS-BRM [34]	$2.46r_s$
AMTI [35]	$1.75r_s$
Munich [36]-[37]	$1.67r_s$
Leeds Mk I [38]	$1.41r_s$
ISO/DIS 14242-1 [39]	$1.58r_s$
Durham Mk II [40]	$1.59r_s$
Leeds Mk II [41]	$1.57r_s$
ProSim [42]	$1.65r_s$
Walking gait cycle [43]-[7]	$1.65r_s$

Note: r_s is the radius of the spherical articulating surface in mm

Based on Table I, the sliding distance of the walking gait cycle is almost all different; however, it is similar to ProSim hip simulator. It indicates that sliding distance in wear calculation of the total hip prosthesis is significantly considered. Therefore, the wear model of the total hip prosthesis with a specific variable of sliding distance is needed. In this paper, the wear prediction model for the total hip prosthesis with specific variable of sliding distance customized with a wide range of case is proposed. The present linear wear model is a modification of the Archard one. The basic of the current wear model is the contact area when the femoral head penetrates to the acetabular liner such as shown in Fig. 1.

Based on this figure, variables of R_C, R_H, r, h_H, h_C, and h_P are defined as cup radius, head radius, contact radius, head height, cup height and height of penetrating, respectively.

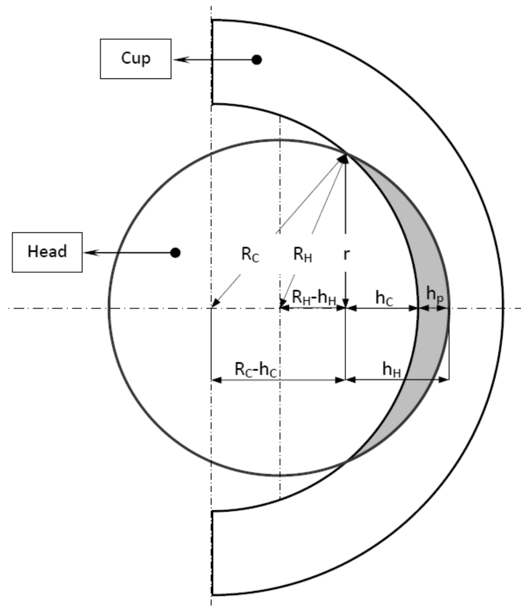
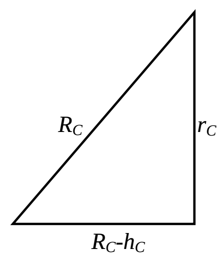


Fig. 1. The geometry of a wearing spherical bearing for linear wear

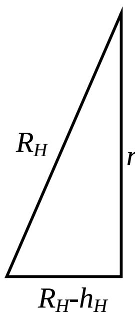
When the femoral head penetrates to the acetabular cup, head height h_H, is obtained, written as Eq. (2). In addition, this penetration forms the contact radius r, where $r = r_C = r_H$:

$$h_H = h_C + h_P \tag{2}$$

Based on Fig. 1, it can be simplified to be two triangles, therefore it can be solved with Pythagoras theorem to find variables r_C and r_H, and next, it will get Eqs. (3)-(4):



$$\begin{gathered} r_C^2 = 2R_C h_C - h_C^2 \\ r_C^2 = 2R_C h_C \quad \text{for } h_C^2 << R_C \end{gathered} \tag{3}$$



$$r_H^2 = 2R_H h_H - h_H^2$$
$$r_H^2 = 2R_H h_H \quad \text{for} \quad h_H^2 << R_H \tag{4}$$

Eq. (2) is substituted to Eq. (4), and Eq. (5) is obtained:

$$r_H^2 = 2R_H h_C + 2R_H h_P \tag{5}$$

h_C can be found by considering Eqs. (3) and (5), Eq. (6) is obtained:

$$h_C = \frac{R_H h_P}{R_C - R_H} \tag{6}$$

Substituting Eq. (6) to Eq. (2), Eq. (7) is obtained:

$$h_H = \frac{R_C h_P}{R_C - R_H} \tag{7}$$

The half-contact area between two conforming surfaces is described by van Beek [44], as shown in Eq. (8):

$$h_H \approx \frac{r_H^2}{2R_H} - \frac{r_C^2}{2R_C} = \frac{r^2}{2}\left(\frac{1}{R_H} - \frac{1}{R_C}\right)$$
$$= \frac{r^2}{2}\left(\frac{1}{R^*}\right) = \frac{r^2}{2R^*} \tag{8}$$
$$r^2 = 2R^* h_H$$

where R^* is the effective contact radius:

$$R^* = \frac{R_H R_C}{R_C - R_H}$$

By dividing the left-hand sides and the right-hand side of Archard wear model in Eq. (1) by the real area of contact (Fig. 1), the relation for linear wear h_H can be obtained

$$\frac{h_H}{L} = K_W PN \tag{9}$$

The differential form of Equation (9) is given by:

$$\frac{dh_H}{dL} = K_W PN \tag{10}$$

where P is contact pressure and quoted in N/mm^2, as shown in Eq. (11):

$$P = \frac{F}{\pi r^2} \tag{11}$$

In order to simplify the calculation, the applied force "F" is constant for every time or gait phase, where the applied force is obtained from the peak force in the gait phase. Fig. 2 illustrates the applied force as a function of the time/gait phase.

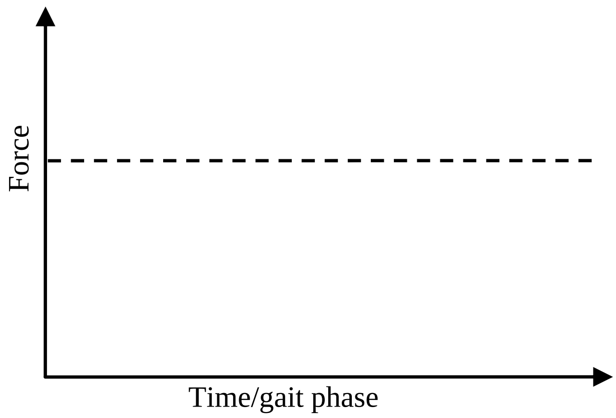


Fig. 2. The applied force "F" curve with time or gait phase

Substituting for P using Eq. (11) and further substitution for the contact radius from Eq. (8) into Eq. (10), so that:

$$\frac{dh_H}{dL} = K_W \frac{F}{\pi\left(2\frac{R_H R_C}{R_C - R_H} h_H\right)} N \tag{12}$$

Integrating h_H with respect to L, thus:

$$\int h_H \, dh_H = K_W \frac{F}{2\pi \frac{R_H R_C}{R_C - R_H}} N \int dL$$
$$\frac{h_H^2}{2} = K_W \frac{F\left(R_C - R_H\right)}{2\pi R_H R_C} LN \tag{13}$$

Substituting Eq. (7) to Eq. (13), Eq. (14) is obtained:

$$h_P = \sqrt{\frac{K_W F\left(R_C - R_H\right)^3 LN}{\pi R_C^3 R_H}} \tag{14}$$

Looking at the sliding distance, L for a walking gait cycle can be obtained from Table II, where r_s is equal to R_H, so that:

$$L = 1.65R_H \quad (15)$$

The final equation of linear wear for walking activity is showed in Eq. (15), where h_P is the penetration or linear wear in mm:

$$h_P = \sqrt{\frac{K_W F \left(R_C - R_H\right)^3 1.65 R_H N}{\pi R_C^3 R_H}} \quad (16)$$

The present linear wear model has been developed to determine volumetric wear or wear loss. The basic of the volumetric wear model is the linear wear or height of penetrating obtained from Eq. (16). The geometry of a wearing spherical bearing for volumetric wear can be seen in Fig. 3. Based on this figure, variables of d and x are defined as the distance of center point head and cup and distance of center point of the cup to the boundary of contact radius, respectively. Eq. (26) is the equation for converting linear wear to volumetric wear. The principal aim of Eq. (25) is to calculate wear volume based on wear depth obtained from Eq. (16). The basic principle of the lost volume is the volume formed by the line h_H reduced by the volume created by h_C line when penetration, (Fig. 3). The volume formed by the line h_H is such as in Eq. (25), while the volume created by h_C line is such as Eq. (26). Further, Eq. (25) is reduced by Eq. (24) based on Eq. (25), so that the volumetric wear model is such as in Eq. (26).

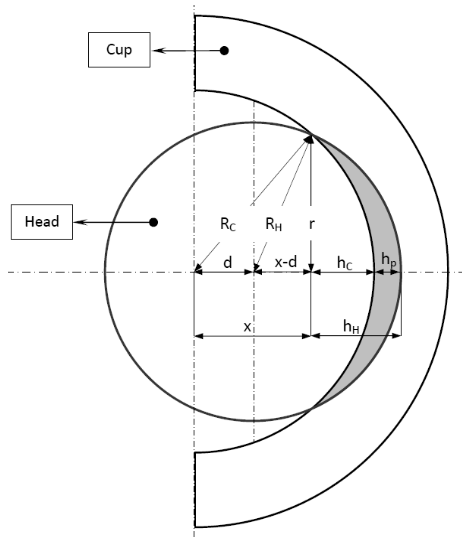


Fig. 3. A geometry of a wearing spherical bearing for volumetric wear

Based on Fig. 3:

$$d = \left(R_C - R_H\right) + h_P \quad (17)$$

Using Pythagoras theorem, the following can be obtained:

$$x^2 + r^2 = R_C^2 \rightarrow r^2 = R_C^2 - x^2 \quad (18)$$

$$\left(x - d\right)^2 + r^2 = R_H^2 \quad (19)$$

Substituting Eq. (18) to Eq. (19):

$$\left(x - d\right)^2 + \left(R_C^2 - x^2\right) = R_H^2$$

$$x^2 - 2xd + d^2 + R_C^2 - x^2 = R_H^2$$

$$x = \frac{d^2 - R_H^2 + R_C^2}{2d} \quad (20)$$

If $h_C = R_C - x$, then:

$$h_C = R_C - \left(\frac{d^2 - R_H^2 + R_C^2}{2d}\right)$$
$$h_C = \frac{2dR_C - d^2 + R_H^2 - R_C^2}{2d} \quad (21)$$

Substituting Eq. (21) to Eq. (2), the equation of h_H is obtained:

$$h_H = \frac{2dR_C - d^2 + R_H^2 - R_C^2}{2d} + h_P \quad (22)$$

Based on the volume of the spherical cap, if V_H (Eq. (23)) and V_C (Eq. (24)) are the volumetric wear of head and cup, the volumetric wear of penetration V_P (Eq. (26)) is an intersection of V_H and V_C. Based on Eq. (21) and Eq. (22), the volumetric wear V_P can be calculated:

$$V_H = \frac{1}{3}\pi h_H^2 \left(3R_H - h_H\right) \quad (23)$$

$$V_C = \frac{1}{3}\pi h_C^2 \left(3R_C - h_C\right) \quad (24)$$

$$V_P = V_H - V_C \quad (25)$$

$$V_P = \left(\frac{1}{3}\pi h_H^2 \left(3R_H - h_H\right)\right) - \left(\frac{1}{3}\pi h_C^2 \left(3R_C - h_C\right)\right) \quad (26)$$

III. Results and Discussion

III.1. Validation of Wear Modeling with Other Model

Dowson et al. [9] have presented both the data of linear and volumetric wear from experiments on a Charnley hip prosthesis in which a ceramic femoral head has been reciprocated in ultra-high-molecular-weight polyethylene (UHMWPE) acetabular liner, (Table III).

TABLE III
DIMENSION OF THE TEST PROSTHESIS [9]

Components	Materials	Diameters (mm)
Acetabular liner (1)	UHMWPE	32.5458
Acetabular liner (2)	UHMWPE	32.5340
Femoral head (1)	Alumina	31.98
Femoral head (2)	Alumina	31.94

Fig. 4 shows a plot of the penetration of their femoral heads number 1 and 2, into the acetabular liner, i.e., the extent of linear wear as a function of the number of loading cycles.

Besides, Fig. 4 shows a wide range of plot of Dowson, Kauzlarich and the present wear model.

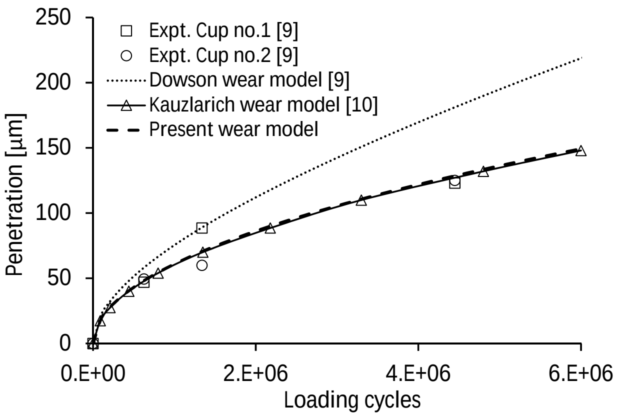


Fig. 4. Plots of present vs Dowson, Kauzlarich wear models and Dowson's experimental data

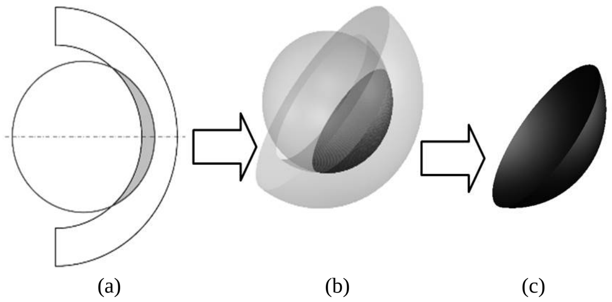
The dash line curve is a plot of Eq. (16) for walking case by using these values together with an amount of K_W equal to 4.49×10^{-7} mm^3/Nm. In Fig. 4, the result of the present wear model shows a good agreement with another wear model.

Eq. (26) is implemented in order to determine the volumetric wear on the acetabular liner. Solidworks CAD software is also used to measure volume loss based on the penetration data in Fig. 4.

The measurement of volumetric wear is performed to be several steps. The first one is creating a sketch of volumetric wear referring to parameters obtained from Eq. (26), as an illustration in Fig. 5(a). The second step is forming part of volumetric wear based on a sketch created in the first step, as the position of volumetric wear in Fig. 5(b). The last step (Fig. 5(c)) is measuring volumetric wear using a measured feature in SolidWorks CAD software.

Fig. 6 shows a plot of volumetric wear as a function of the number of loading cycles. The dash line is a plot of Eq. (26) for the walking case, while the cycle marker is a plot of volumetric wear by CAD software.

Based on this comparison, the present volumetric wear result also shows a good agreement with the volumetric wear measurement by Solidworks CAD software. In other words, the volumetric wear can be obtained using the calculation by Eq. (26) and the measurement by CAD software.



Figs. 5. Measurement of wear volumetric: (a) sketching of wear volumetric based on parameters in Fig. 1; (b) creating of wear volumetric using CAD software; (c) measuring of wear volumetric using a measured feature in Solidworks CAD software

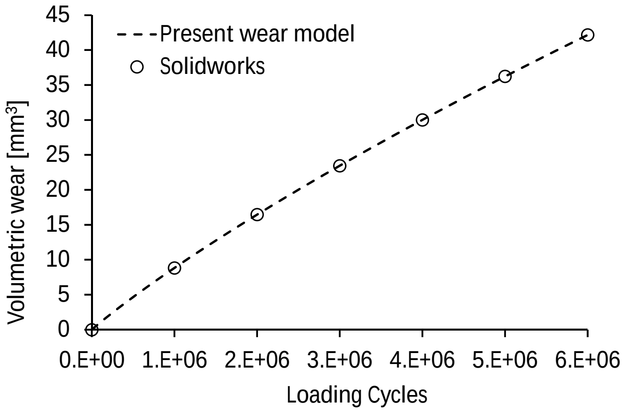


Fig. 6. Plots of volumetric wear between the present wear model and the Solidworks measurement

III.2. The Wear Comparison of Total Hip Prostheses for Salat and Walking Activities

Figs. 7 and 8 show the result of present linear and volumetric wear as a function of loading cycles due to salat activity (in 10 years). The geometries of the acetabular and femoral head are based on the Dowson's experimental data (Table III), whereas wear coefficient is equal to 4.49×10^{-7} mm^3/Nm. The applied load and the sliding distances are obtained from the assumption in the salat gait cycle section. On the other hand, the number of loading cycle is derived from calculating the number of *rak^ahs* in one day until ten years, (Table IV).

TABLE IV
THE CALCULATION OF *RAK^AHS* (CYCLES)

Number of days	Number of *rak'ahs* (cycles)
1	17
30 (1 month)	510
365 (1 year)	6205
3650 (10 years)	62050

In order to obtain information of wear contribution due to salat activity in the total hip prosthesis, both wears due to salat and walking activities are compared. The cycle number of walking activity measured using an electronic digital pedometer, where several researchers have performed it. Seedhom *et al.* [45] have proposed some cycles of of walking about 1 million cycles per year, whereas Schmalzried *et al.* [46] have proposed the most active patient averagely approximately 2.1 million cycles per year. In order to simplify, one million cycles per year are used in this research for walking activity.

Figs. 7 and 8 show a comparison between the result of present linear and volumetric wear as a function of years due to salat and walking activities. These figures describe the wear of total hip prosthesis due to salat and walking activities every year until ten years. Based on this comparison, it can be seen that linear and volumetric wear due to salat activity is lower than wear due to walking activity. The magnitude of linear wear due to salat activity in ten years is around 26 μm, while the amount of linear wear due to walking activity in ten years is approximately 192 μm.

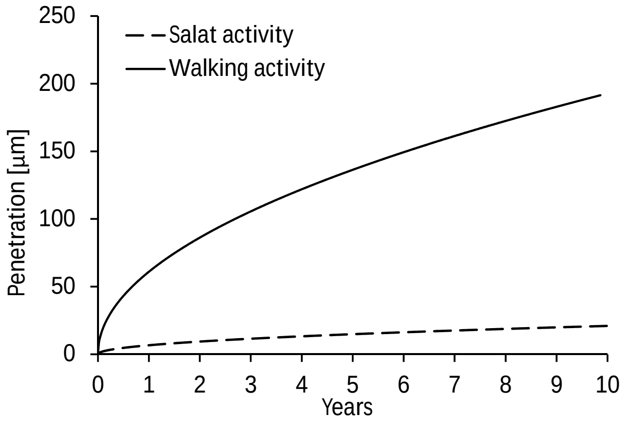


Fig. 7. The prediction of the linear wear of the total hip prosthesis in 10 years

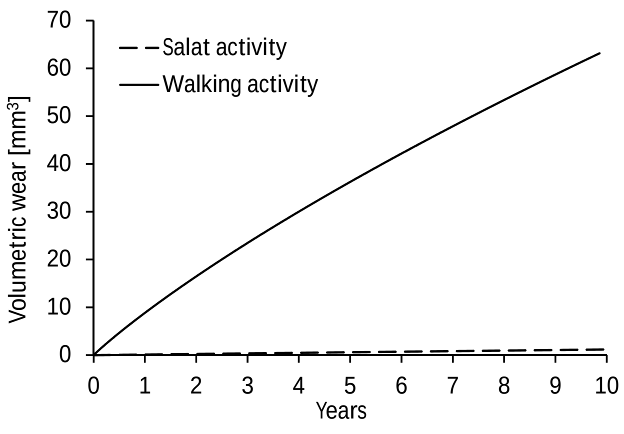


Fig. 8. The prediction of the linear wear of the total hip prosthesis in 10 years

The amount of volumetric wear due to salat activity in ten years is around 1.84 mm^3, whereas the walking activity is approximately 63 mm^3. Based on this phenomenon, the deviations of both linear and volumetric wears are about 86% and 97%, respectively.

IV. Conclusion

In this paper, the new wear formulation of the total hip prosthesis has been proposed. The validation with other wear models has been accomplished to check the accuracy of the present wear model. The result of the current wear model shows a good agreement with other wear models. Besides, the volumetric wear model as development of the linear wear model to predict wear loss on the liner surface has also been proposed. The volumetric wear model has also been validated with wear loss obtained from Solidworks CAD software. Thus, both the present linear and volumetric wears have been used to calculate wear on the liner surface of total hip prosthesis due to salat activity. The geometry of the total hip prosthesis and the wear coefficient of UHMWPE material have been obtained from literature, whereas, the applied load and sliding distances have been obtained from salat gait cycle. The results are presented in linear wear and volumetric wear as a function of number cycles and years. The results show that the linear wear due to salat activity is lower than walking activity because the intensity of salat activity is lower than walking activity.

However, the combination of both wears due to walking and salat activities needs to be considered. When the wear on the hip prosthesis is based solely on the effect of the salat movement, the wear is minimal or negligible within ten years. However, when the wear on the hip prosthesis is a combination of the salat and walking activities, then the effect is more significant in 10 period years. Therefore, this study has used as a first step in assessing the wear on hip prosthesis due to the salat movement. However, the present wear model can only predict wear on the liner surface of the unipolar hip prosthesis. The current wear model cannot predict wear on the liner surface of the dual mobility hip prosthesis.

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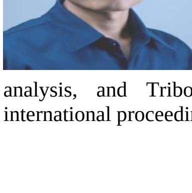

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