NEW STUDY ON FRICTION IN A MOM TOTAL HIP PROSTHESIS WITH BALLS IN SELF-DIRECTED MOTION

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Abstract

Although Metal-On-Metal (MOM) Total Hip Prostheses (THP) with self directed balls have as their greatest advantage the replacement of the specific regular hip prostheses sliding movement between the femoral head and the acetabulum socket with the rolling movement between the balls, the socket and the femoral head, the lubrication side of the process is still not well known. Tests with balls on a flat rig showed maximum values for the friction coefficient of under 0.05 while studies of lubrication with saline solution have indicated an EHL lubrication schedule, with a minimum value for the thickness of the lubrication film (h_{min}), measured through the contact resistance methodology, of 0.06 µm. There are obvious trends of seizure in the operation of these prostheses. However, preliminary studies on lubrication in Metal-On-Metal prostheses also showed a clear seizure tendency. For the purposes of the present study we opted for changing the constructive version, adopting a modified motion Omnitrack solution, adapted for use in an artificial hip joint. After testing on an experimental device, the results were spectacular. The minimum friction coefficient value is 0.007, while the maximum value reaches 0.02.

Keywords: *Metal on metal total hip prosthesis, balls, self directed movement, lubrication, friction coefficient.*

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1. INTRODUCTION

Given the need to continuously improve the sustainability of total hip prostheses, advances in the technology of biocompatible metal alloys and processing techniques of the surfaces, potential metal-on-metal (MOM) of total hip replacements was recently reconsidered. Although it was often reported that the first generation of hip implants used in the 1970s was a failure due to a high friction moment, the new generation implants showed an encouraging clinical performance in the short and medium term, with little wear and a long lifespan, hence their increased use. In a very recent paper, Hsu et al [1] have critically evaluated the nature of friction. Their results suggest that under lubricated conditions, when surfaces are separated by a full fluid film, the friction is mostly influenced by the viscous shear resistance. Since 1970, in a reference paper, D. Dowson [1] was the first to appreciate that the lubrication of MOM total hip prosthesis is elastohydrodynamic (EHL). This approach is also widely considered today.

Leiming Gao et al [3] presented a simulation of the elastohydrodynamic (EHL) lubrication of a metal-on-metal (MOM) total hip implant, considering both the equilibrium state and the physiological load transient state in order to easily and accurately reproduce loading and 3D movement during the gait cycle in all three directions.

In 2012, I. Páczelt, S. Kucharski and Z. Mróz [4] published an experimental and numerical analysis of near-constant wear process of sliding of a spherical indentor, finding that the law of wear of Holm and Archard – which links the total volume of wear with the normal load and the sliding length, can be conveniently used in practical applications and does not require prior knowledge of the contact area.

S. Sharma et al [5] presented an interesting optical microscopic method for the determination of ball-on-flat surface linearly reciprocating sliding wear volume.

I. Iliuc [6] analyzed the wear and micropitting of a steel ball sliding against a TiN coated steel plate in both dry and lubricated conditions. Also, I. Iliuc and M. Jokl presented a comparative investigation of the sliding wear mechanism in lubricated steel-on-steel and diamond-on-steel friction couples [7]. Claire Brocket et al published an analysis of the friction of total hip replacement with different bearings and under different loading conditions [8].

F. Munteanu and P. Botez [9] studied the variation of the friction factor trough the gait cycle in an UHMWPE-CoCrMo hip endoprosthesis. In 2010, Teymour Javaherchi [10] published a review of Spalart-Allmaras turbulence model and its modifications. P. R. Spalart and S. R. Allmaras [11] presented in 1994 a one equation turbulence model for aerodinamic flows. This model is still in use today for simulating the liquid flows, and moreover, it is being continuously updated by the NASA [12].

G. E.Moralles-Espejel and A. Gabelli [13] studied the behaviour of indentation marks in rolling-sliding elastohydrodynamically lubricated contacts and P. J.Bills et al, published a volumetric wear assessment on recovered metal-on-metal hip prostheses and measured the impact of measurement uncertaintly [14].

P. M. Lught and G. E.Moralles-Espejel [15] have published a review of elasto – hydrodynamic lubrication theory, and Qingen Meng, Leiming Gao, Feng Liu, Peiran Yang John Fisher and Zhonming Jin [16] reported that the diameter (and its tolerance) of the bearing surfaces of metal-on-metal hip implants and the structural supports are key factors that reduce dry contact pressures and improve the performance of hydrodynamic lubrication.

With all the studies and improvements presented, wear continues to be present in the latest generation of THP-MOM. Nowadays, design solutions for Total Hip Prostheses are diverse, encompassing improvements in the materials used for prostheses elements, geometrical reshaping and/or tribological load transfer path. From this perspective, Total Hip Prostheses with rolling balls have been found to be a viable alternative design to current industrial products, due to the low friction generated by the rolling contact versus the friction caused by sliding (as is now used in most industrial designs).

Different designs of Total Hip Prostheses with rolling bodies have been developed in order to improve the tribological performances of the artificial joint. We could mention here the ball train design proposed by Katsutoshi and Kiyoshi [17].

In another paper [18], the authors focus on the original design proposed by them in [19], a MOM THP with self directed rolling balls (SDBJ) - this constructive solution has been described in detail in [20]. Although experimental tests highlighted very low values of the rolling friction coefficient (below 0.05), seizure tendencies have been reported [20].

In the present research we used an experimental device with two total hip prostheses joints mounted in anatomical position, whose movement reproduces the flexion - extension movement of the of human hip joint [21]. The results are very promising.

2. MATERIALS AND METHODS

The device presented in Fig. 1 has been designed for experimental tests. The main features of this device are:
- Simultaneous/alternative measurements of of the friction coefficient;
- Perfect timing in the kinematic and dynamic simulation of the hip joint;
- Compliance with the angle formed by the load axis and the oscillation axis.

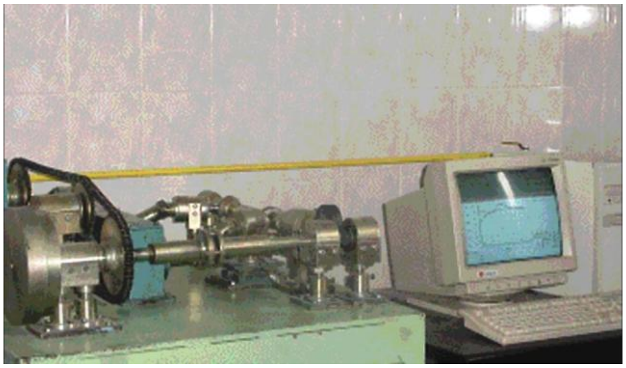


Fig – 1: The testing device.

Figure 2 shows the kinematic diagram of this device. The device was built in such a way that the acetabular double piece is supported by only the two femoral heads that oscillate in two directions, similar to a hip (Figure 2, pos. 9).

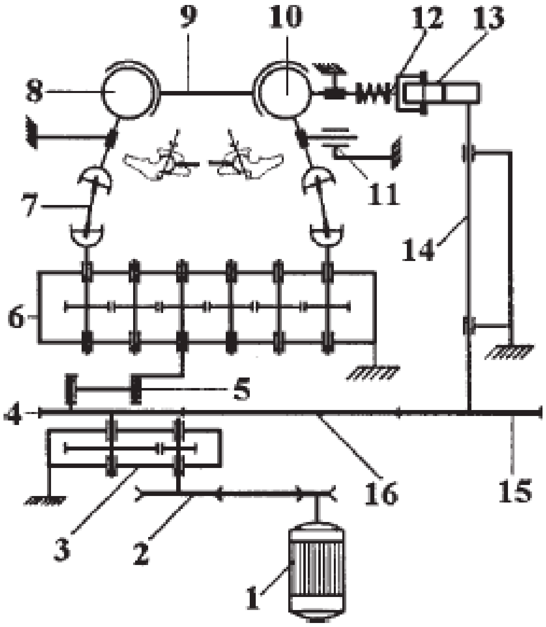


Fig - 2. Kinematic diagram of testing device: 1 - electromotor; 2 - trapezoidal belts; 3 - reccurent reducing gear; 4 - wheel driving chain; 5 - gear box; 6 - gear reducer recurrent (periodic); 7 - universal joint; 8, 10 - femoral heads; 9 - acetabular double piece; 11 - shaft; 12 - coupling with wedge and pull spline; 13 - cam; 14 - shaft; 15 - driven sprocket; 16 - Gall's chain.

Figure 3 shows an image of the acetabular double piece, with femoral heads fitted.

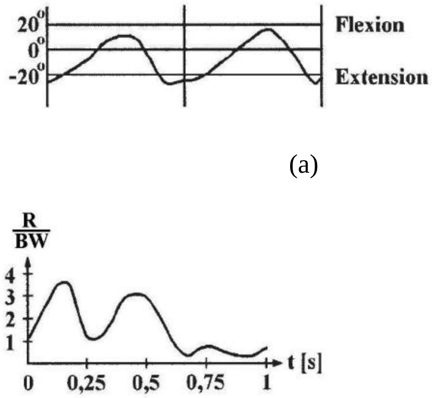
Fig 3 - Acetabular double piece (pos. 9 in figure 2).

You can also see that the acetabular double piece moves at the same time as the femoral heads due to friction (Fig. 2, pos. 8 and 10).

The measured friction torque is a projection of the real torque, the latter resulting from the calculations. A cam - till - helicoidal compression spring (Fig. 2, Pos. 12) accomplishes the specific load to the hip articulation. The cam (Fig. 2, pos. 13) was synthesized according to the loading diagram (Fig. 4b).

The cam was rocked in the rotation of the chain (Fig. 2, Pos 4, 15, 16) and a shaft (Fig. 2, pos. 14). The flexion-extension movement was described by a quadrilateral gearing (Fig. 2, pos. 5), which has turned the chain wheel rotation (Figure 2, pos. 4) into an oscillation.

This movement had a 1 Hz frequency (achieved by reducing the angular velocity generated by the electric motor, position 1, through trapezoidal belts transmission, position 2 and a repeating gear reducer, position 3).

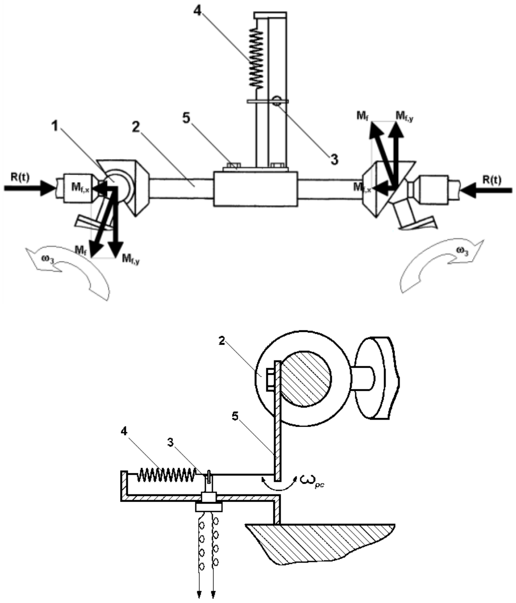


(a)

(b)

Fig 4. (a) Variation of the flexion – extension ower two gait cycles and (b) variation of the ratio R / BW during a normal gait cycle.

Oscillation has been transmitted to the femoral head by means of a chain with bolts, with the ratio of 1:1 (Figure 2, item 5) and a cardanic universal coupling. For each gait cycle determinations of the friction coefficient were made for both the self directed balls joint (SDBJ) and for a type of Omnitrack® solutions movement, modified and adapted to the purpose (MOSMJ).



To acquisition board

Fig 5. Representation of the measuring method of moment of friction: 1: femoral head; 2: the double acetabular piece; 3: potentiometer; 4: helicoidal traction spring; 5: rigid plate mounted on double acetabular piece.

The determinations were made taking into consideration the human gait characteristic movements, namely:

- The way in which the angular velocity of the femoral head varies;
- The way in which the load varies on the hip joint (loading and unloading cycle of the hip joint).

Our method is based on the movement of the rigid plate that compresses the shown spring and this in turn leads to a variation in the electrical tension captured by a movement translator, in this case a computer acquisition board.

The measuring method for the friction coefficient is shown in Figure 5. It’s worth nothing that these experiments were conducted using SBF (simulated body fluid). The fluid had the density of 1118 kg/m3 and 0.8 kg/ms viscosity. The displacement variation is shown in Figure 6.

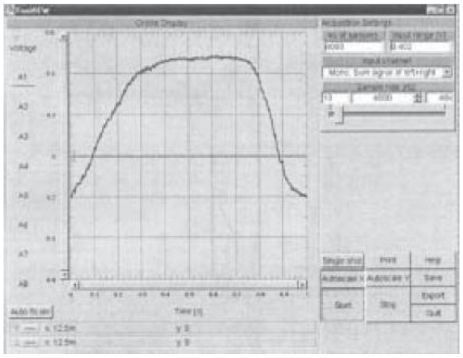


Fig 6. Variation of x displacement during a complete gait cycle.

The main purpose of this study was to determine the friction coefficient and to try to establish the optimum lubrication conditions.

We could express the experimentally determined dissipated power associated with a full gait cycle as:

$$P_{DE} = M_{fE} \cdot \left|\omega_{pa}\right| \tag{1}$$

Where:
PDE is the experimentally determined dissipated power associated with a full gait cycle; MfE is the experimental friction moment, and ωpa – the angular (variable) velocity of the acetabular component. The angular velocity is implicitly taken as positive for the purposes of obtaining a positive dissipated power in the cycle.

The measured friction moment is:

$$M_{fm} = k \cdot x \cdot l \tag{2}$$

Where:
k – the spring’s elasticity parameter (k =14 N/mm);
x – the spring’s deformation or the plate displacement;
l – the length of the rigid plate (l = 63 mm).

The rigid plate displacement, x, has been experimentally determined as being the double of Mfx (figure 5). The angle of the resultant R and the flexion-extension axis is 700 while the experimentally determined friction moment, MfE, is:

$$M_{fE} = \frac{1}{2 \cdot \cos 70^0} \cdot M_{fm} = \frac{k \cdot x \cdot l}{2 \cdot \cos 70^0} \tag{3}$$

The experimental dissipated power is the scalar product of the friction moment and the angular velocity of the double acetabular piece, ωpc:

$$P_{DE} = \overline{M}_{fE} \cdot \overline{\omega}_{pc} = M_{fE} \cdot \left|\omega_{pc}\right| \cdot \cos 70^0 \Rightarrow$$
$$P_{DE} = \frac{1}{2} \cdot k \cdot x \cdot l \cdot \left|\omega_{pc}\right| \tag{4}$$

The angular velocity of the acetabular piece is expressed in relation to the extremities of the rigid plate as $v_{\dot{r}}$:

$$\left|\omega_{pc}\right| = \frac{v_l}{l} \cdot \frac{\left|\Delta x\right|}{\Delta t}. \tag{5}$$

This leads us to express the dissipated power as:

$$P_{DE} = \frac{k \cdot x}{2} \cdot \frac{\left|\Delta x\right|}{\Delta t}. \tag{6}$$

The experimental dissipated power must be equal to the theoretical power:

$$P_{DT} = P_{DE} \tag{7}$$

The above equality allows us to obtain the friction coefficient:

$$\mu = \frac{P_{DE}}{P_{fTE}} \tag{8}$$

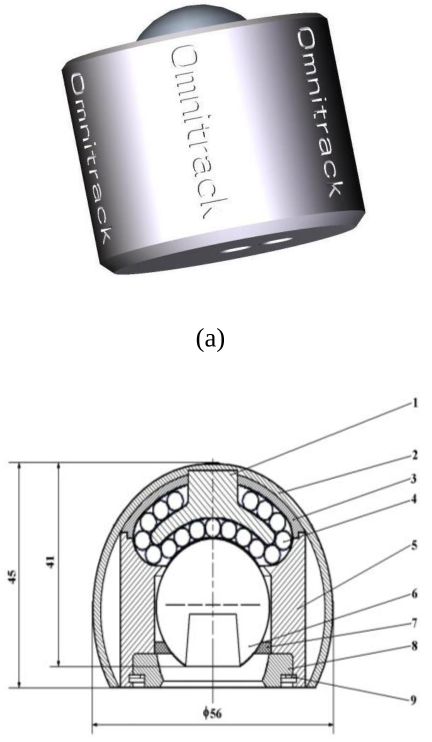
where PfTE is the theoretical power dissipated through friction.

Therefore:

$$\frac{1}{\mu} = \frac{P_{fTE}}{P_{DE}} = \frac{1}{\mu_E} \tag{9}$$

Where μE is the elastic component of the friction coefficient

Fig 7. Acetabular cup - femoral head joint with balls in self directed movement (SDBJ).



(a)

(b)

Fig 8. Stainless steel 316L Omnitrack joint (a) with low friction (μ = 0.005), maximum speed 2 m/s, temperature range -30 0C to + 160 0C, high shock resistance and (b) new acetabular - femoral joint (MOSMJ) based on the modified Omnitrack movement solution : 1 - balls guide; 2 - outside casing; 3 - superior handle; 4 - ball; 5 - lower handle; 6 - femoral head; 7 - silicone rubber linings; 8 - lid; 9 – "Spiralax" ring.

Both the Total Hip Prostheses with Self Directed Ball Joint (SDBJ) – Fig. 7, as well as a new prostheses (MOSMJ) – Fig. 8, have been tested, the latter being based on a constructively modified Omnitrack™ [22] movement solution.

We've named this new device a "femoral joint with self directed balls in Omnitrack® movement solution, modified (OSMJM)". The modified joint is a type 9030 [22], all of its components being manufactured out of medical grade SS316L stainless steel in order to provide very low friction (μ = 0.005). For a maximum 2 m/s velocity the joint can sustain a maximum 375 kg load and can optimally function between -30 0C and + 160 0C. The joint is highly resistant to shocks.

In order to obtain the modified joint (Fig. 8a), the exterior component of the Omnitrack solution has been processed by turning so that it could fit into a medical grade 316L stainless steel casing and create the cocso – femural prosthetic joint. The Omnitrack™ movement solution (Fig. 8b) also had its functioning position changed by 1800.

The ball guide, pos. 1 in Fig. 8(b), has been manufactured out of AmAlOx ceramic alumina in order to improve its seizure resistance. AmAlOx 87 alumina (Astro Met Aluminum Oxide) comes from Astro Met, Inc., Cincinnati, OH, USA. It's a high purity 99.8% aluminum oxide (alumina) ceramic which has been originally developed for critical load bearing medical implants, and optimized for maximum wear and corrosion resistance. A high density, diamond like hardness, fine grain structure and superior mechanical strength are its unique properties that make the AmAlOx alumina the appropriate material for demanding applications. The typical properties of AmAlOx 87 alumina include a bulk density of 3.97 g/cm3, flexural strength of 70 KPSI (482 MPa), Vickers Hardness of 2000 and a grain size of 2 microns.

AmAlOx 87 alumina has an unusually small grain size for an alumina ceramic and this enables extremely tight tolerances and surface finishes of 2 microinches Ra to be achieved when the proper finishing techniques are being used.

3. RESULTS AND DISCUSSION

Figures 9 and 10 detail the real time variation of the friction coefficient in relation to the angualr velocity and the load during a full 1 second gait cycle on the testing device shown in Figure 1. The maximum load used was 3000N for an angular velocity of 1 step / second. Comparing the two diagrams allows for a few observations.

The minimum values of the friction coefficient for the SDBJ and the OSMJM joints are 0.009 and 0.006 respectively. The maximum values of the friction coefficient for the SDBJ and the OSMJM joints are 0.031 and 0.02 respectively.

The average values of the friction coefficient for the SDBJ and the OSMJM joints are therefore 0.022 and 0.016 respectively.
The sudden decreases in the friction coefficient values (the troughs) are due to the almost frictionless rolling of the balls on the femural head. The two peaks are representative of the "heel strike" [21] phase in the gait cycle. Peaks occur when a greater number of balls become engaged in motion and slide on the femoral head.

Figs 9 and 10 shows a time comparison between the friction coefficient, the angular velocity modulus and the load, SDBJ and in the low friction Omnitrack joint, OSMJ.

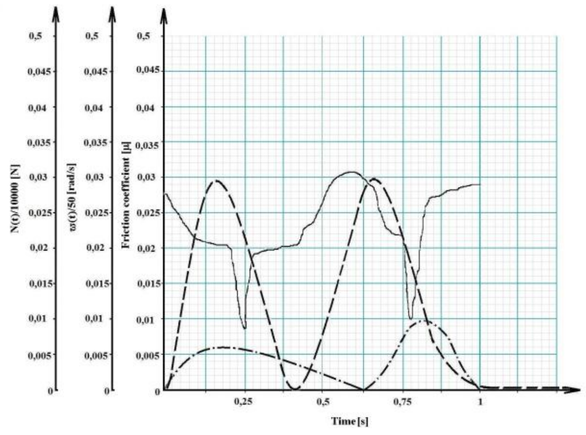


Fig 9. Comparison between friction coefficient and the angular velocity modulus, for the self directed balls acetabular - femoral joint (SDBJ) in Figure 7. It is worth noting that there is an inverse dependency between the friction coefficient and the load and a direct dependency with the angular velocity. —— μ (t); — · — N (t) / 10000 [N]; · · · · ω (t) / 25 [rad /s]

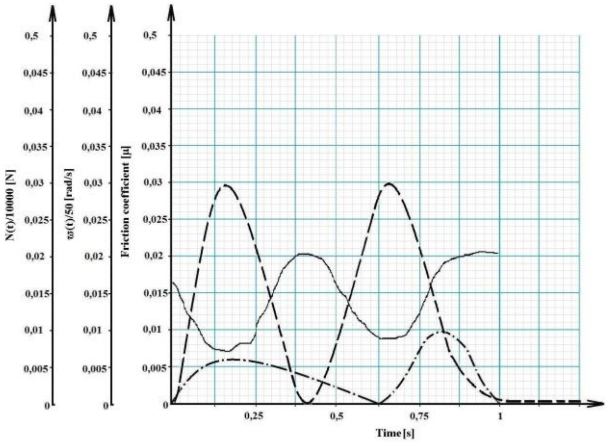


Fig. 10. Comparison between friction coefficient and the angular velocity modulus, in the case of the acetabular - femoral joint with self directed balls in the modified Omnitrack® solution (OSMJM). It is worth noting that there is an inverse dependency between the friction coefficient and the load and a direct dependency with the angular velocity. —— μ (t); — · — N (t) / 10000 [N]; · · · · ω (t) / 25 [rad /s].

The peculiar shape of the curve that plots the variation of the friction coefficient is due to the overlapping of the friction phenomena specific to the sliding and rolling movements, respectively.

It's a well known fact that the velocity and the load are the main factors that influence the friction coefficient values. Consequently, given the afore-mentioned experimental conditions, a periodical variation was expected and occured in the recorded results, due to the rolling movement of the tested devices.

Studying the periodic nature of the friction coefficient values allows us to observe threefold increases in its values. We can explain this through the fact that the recorded coefficient values are the sum of the effects of the rolling motion and the sliding motion between the balls and the surfaces they come in contact with. What we are dealing with can therefore be called a global friction coefficient that sums up the effects of the different motions. The overlap of the effects is all the more visible in the SDBJ joint, where the sliding of the balls in the constructively designed free space that prevents the seizure of the ball array leads to slightly greater values for the global friction coefficient.

It's worth noting that the smallest values for the friction coefficient have been recorded in areas close to maximum loads, where a predominantly rolling motion takes place.

The recorded minimums for the two experimental devices also allow us to observe different contributions of the sliding motions, although the values of the friction coefficient are very close.

In the OSMJM joint we also observe that, apparently, the angular velocity is not a main factor in the change in friction coefficient values, these being, in fact, inversely proportional to the load – we recorded minimum coefficient values for both minimum and maximum angular velocities.

The angular velocity becomes an important influencing factor for the SDBJ joint due to the overlap of the sliding and rolling motion effects. Thus, we recorded sudden decreases in the friction coefficient for maximum velocities and substantial loads – indicative of a predominantly rolling motion effect.

4. CONCLUSIONS

Our research on the friction and lubrication in rolling motion hip prostheses allows us to conclude that:
- The friction coefficient is dramatically reduced compared to a classic sliding motion of the hip prostheses (Ti6Al4V/UHMWPE), whose minimum coefficient value is 0.05;
- the recorded values for the friction coefficient in the self-directed balls join (SDBJ) range between 0.009 and 0.031, while those particular to the modified Omnitrack solution (OSMJM) range between 0.006 and 0.02;
- The average friction coefficient recorded value for the Omnitrack® modified solution (OSMJM) is 0.016;
- Maximum values correspond to the "heel strike" phase in the gait cycle;

- There’s an overlap of friction phenomena specific to the rolling and sliding motions. This leads to peculiar changes in the friction coefficient values. We plan to investigate these variations in future research.
- rolling motion THPs are a viable solution where sliding motion THPs are inappropriate due to the user’s high body mass.

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BIOGRAPHIES

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