

# Wear Performance Analysis of UHMWPE for Total Knee Arthroplasty

A Comparative Study of Materials from Different Sources

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## ABSTRACT

Ultra-High Molecular Weight Polyethylene (UHMWPE) is a key material in orthopedic implants, particularly in Total Knee Arthroplasty (TKA), due to its excellent wear resistance and biocompatibility. This study aimed to evaluate and compare the wear behavior of domestically produced UHMWPE (PIN A) with commercially available products from China (PIN B) and the United States (PIN C). Wear tests were performed using a pin-on-disc tribometer under dry conditions to determine the wear volume, the wear rate, and the wear coefficient. Microstructural analysis was also conducted using Scanning Electron Microscopy (SEM), and hardness was measured with a Shore D durometer. The results showed that PIN A exhibited superior wear performance, having the lowest wear width of 1.198 mm at 4500, as well as the lowest wear volume and wear rate. Another significant observation was that the wear coefficient for PIN A was the lowest at  $8.35 \times 10^{-7}$  mm<sup>3</sup>/Nm, reflecting the best resistance to material loss under friction. PIN B showed a moderate wear coefficient of  $1.19 \times 10^{-6}$  mm<sup>3</sup>/Nm, while PIN C had the highest with  $1.83 \times 10^{-6}$  mm<sup>3</sup>/Nm, indicating the poorest wear resistance. SEM micrographs also confirmed that the microstructure of PIN A had a compact, layered, and fibrous morphology, which contributed to its superior mechanical performance. The trend shows that domestic UHMWPE can match or exceed the performance of imported materials when subjected to proper processing and supports the potential application in clinical orthopedic procedures.

*Keywords-UHMWPE; wear resistance; TKA; pin-on-disc; biomechanical properties; microstructure evaluation*

## I. INTRODUCTION

Ultra-High-Molecular-Weight Polyethylene (UHMWPE) is a type of polyethylene with a molecular weight range of 3.5 to 7.5 million g/mol. The attributes make UHMWPE a part of the high-molecular-weight polyethylene often used in arthroplasty procedures [1]. The polymer is popular for its remarkable strength, abrasion resistance, and low coefficient of friction, which make it perfect for a variety of uses across several industries [2, 3].

Total Knee Arthroplasty (TKA), which is known as total knee replacement, is a surgical procedure to remove and replace damaged or diseased parts of the knee joint with artificial components [4-7]. This procedure is commonly performed to relieve pain and improve function in patients with severe arthritis or other conditions that affect the knee joint [8]. However, the success of TKA is significantly dependent on the design of the implants and the materials used, such as UHMWPE [9-15].

UHMWPE is a key material in knee arthroplasty implants due to its excellent wear resistance and biocompatibility [10, 16-18]. Its low-friction properties help reduce the wear and tear on the implant, leading to improved longevity and general success of the procedure [19, 20]. Moreover, UHMWPE has low levels of inflammation and tissue reaction and is an effective choice for TKA [9, 13, 21, 22]. The development and improvement of UHMWPE materials have played a significant role in the advancement of the field of knee arthroplasty and in the improvement of patient outcomes [23, 24]. However, the long-term performance of UHMWPE implants is possibly subject to different factors, such as patient activity level and general health, potentially affecting the success of the procedure [25-27].

Several countries, such as the United States, Germany, China, and India, manufacture TKA implants in line with ISO and ASTM standards, but the focus is mainly on testing and characterization methods without defining explicit performance criteria [28, 29]. However, most of the existing implant

products are developed based on anthropometric data, lifestyle, and cultural practices of the populations in these countries. Consequently, this makes the designs not fully in line with the unique physiological characteristics and daily activity patterns of Indonesian patients. In particular, Indonesians frequently perform activities that require deep knee flexion, such as sitting cross-legged, squatting, or kneeling during religious practices [30]. These movements require a higher flexion angle and greater implant adaptability than what is typically accommodated by conventional TKA designs [31]. Therefore, there is a strong necessity for implant innovations specifically customized to Indonesian anatomical dimensions and socio-cultural needs to ensure both functional performance and long-term durability.

The trend leads to the development of a TKA design that is capable of achieving a high flexion angle for social-cultural and religious activities for the benefit of the Indonesian population [32-34]. The application of UHMWPE in knee replacement has transformed orthopedic surgery and is opening new avenues for better patient care and results, considering all factors. Thus, the purpose of this study was to evaluate the wear of UHMWPE on TKA implants compared to currently available Chinese and US products.

## II. MATERIALS AND METHODS

UHMWPE powder material was processed using compression molding at 230°C, 14.2 kg/cm<sup>2</sup>, and 15 s of holding time. The processed material is referred to as PIN A. Meanwhile, UHMWPE from TKA components, currently available for purchase and manufactured in China (PIN B) by Chunli and the United States (PIN C) by Smith & Nephew (Figure 1), were used for a comparison. UHMWPE was produced in the form of a pin, as shown in Figure 2, using AISI 316L as the disc material on the tribometer and 0.24 μm surface roughness. The densities of PIN A, PIN B, and PIN C were 0.90 g/cm<sup>3</sup>, 0.98 g/cm<sup>3</sup>, and 0.99 g/cm<sup>3</sup>, respectively, while the surface roughness was 0.77 μm, 0.75 μm, and 0.74 μm.

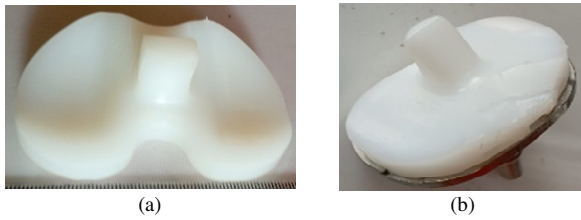


Fig. 1. TKA UHMWPE components: (a) Chunli, (b) Smith & Nephew.

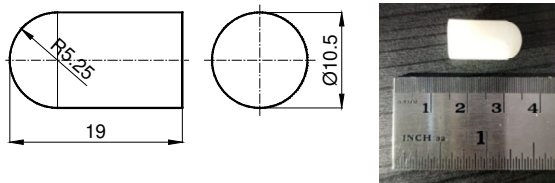


Fig. 2. UHMWPE pins.

The wear resistance of the UHMWPE pins was tested using a tribometer pin-on-disc [35, 36]. A weight of 12.1 N and a rotational speed of 60 rpm were used, and the test was conducted in dry conditions without oil. The process was implemented 15 times, each for 300 s. Moreover, three wear tests were applied to each product, and the average was calculated. The wear volume and wear rate were determined using the Buyer equation [37], while the wear coefficient was determined through the Archard equation [38]. Therefore, wear volume, wear rate, and wear coefficient were calculated using:

$$V = \frac{\pi}{64} \times \frac{w^4}{R} \quad (1)$$

$$W = \frac{V_i - V_s}{t} = \frac{V}{t} \quad (2)$$

$$V = k_D \times F_N \times s \quad (3)$$

where  $V$  is the wear volume,  $W$  is the wear track diameter on the pin,  $R$  is the ball radius indenter,  $k_D$  is the wear coefficient,  $F_N$  is the normal load,  $s$  is the sliding distance,  $W$  is the wear rate,  $V_i$  is the initial volume,  $V_s$  is the end volume, and  $t$  is time.

Micro-images were used to measure the path or wear track diameter on the pin. The wear width on the pin is clearly shown in the images, allowing for accurate measurement and analysis of the wear behavior. The wear test generally confirmed the durability and effectiveness of the UHMWPE pins in dry conditions. The results of the wear test were confirmed using a Shore D-type durometer plastic hardness tester in line with ASTM D2240 standards. The durability and quality of the products under examination were subsequently assessed by comparing the wear test results to industry norms. The requirements of the ASTM D2240 standard for accurate and dependable wear test results were satisfied by the Shore D-type durometer plastic hardness tester. The microstructure of the UHMWPE pins was further examined using Scanning Electron Microscopy (SEM) to confirm the hardness test results. This process assisted in identifying any possible areas for improvement and offered a more thorough knowledge of the function of the pins under different circumstances. Moreover, the durability and efficacy of the pins were more thoroughly and accurately assessed by integrating the hardness tester results with SEM analysis.

### III. RESULTS

Figure 3 shows the wear track diameter on PIN A, PIN B, and PIN C after being subjected to friction for 4500 s. PIN A exhibited the smallest wear width at 1221.1  $\mu\text{m}$ , demonstrating the best resistance to friction-induced wear. PIN B had a slightly higher value of 1289.1  $\mu\text{m}$ , which suggests moderate wear resistance. PIN C showed the highest value with 1479.6  $\mu\text{m}$  and reflected the poorest wear resistance. This visual evidence suggests that the material or surface treatment of PIN A offered superior friction resistance compared to PIN B and specifically PIN C.

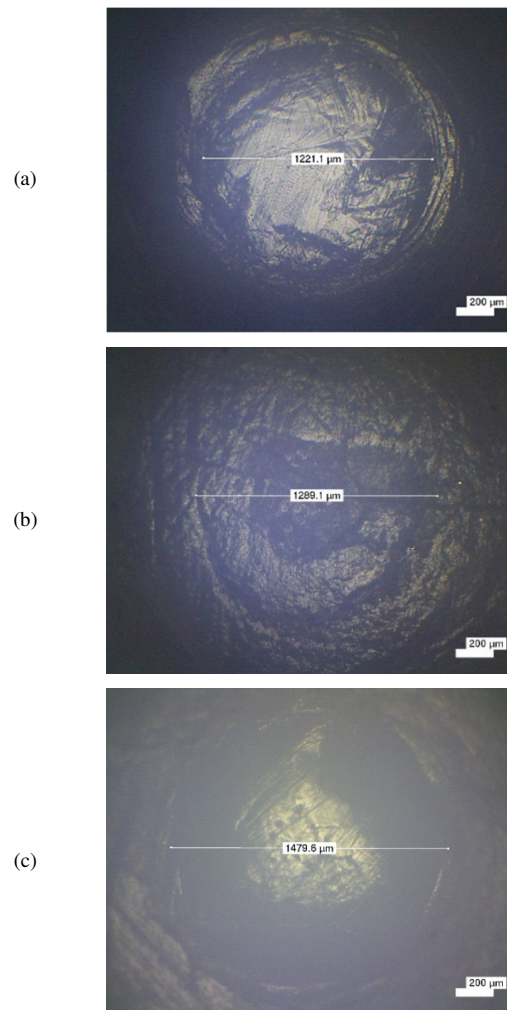


Fig. 3. Wear track diameter of pins for 4500 s: (a) PIN A (1221.1 $\mu\text{m}$ ), (b) PIN B (1289.1 $\mu\text{m}$ ), (c) PIN C (1479.6  $\mu\text{m}$ ).

Table I presents the wear track diameter for the three different pin specimens measured at various times ranging from 300 to 4500 s. PIN A consistently showed the smallest wear track diameter at all time intervals by starting from 1.045 mm at 300 s and gradually increasing to 1.198 mm at 4500 s, reflecting excellent wear resistance. PIN B had moderate wear width values, starting at 1.162 mm at 300 s and reaching 1.311 mm at 4500 s. The values increased steadily over time to show

moderate resistance to wear. However, PIN C exhibited the highest wear width throughout the duration of the test, starting at 1.223 mm and increasing to 1.458 mm. The trend showed poor wear resistance compared to the other two specimens. The data generally showed that the wear width increased with time for all specimens due to continuous friction. Meanwhile, the degree of increase varied, with PIN A being the most wear-resistant, PIN B showing moderate performance, and PIN C having the least resistance to wear.

TABLE I. WEAR TRACK DIAMETER OF PINS

Time (s)	Wear track diameter (mm)		
	PINA	PIN B	PIN C
0	0	0	0
300	1.045	1.162	1.223
600	1.078	1.206	1.239
900	1.087	1.244	1.255
1200	1.103	1.256	1.270
1500	1.120	1.274	1.286
1800	1.124	1.278	1.302
2100	1.128	1.281	1.317
2400	1.132	1.287	1.333
2700	1.136	1.290	1.349
3000	1.143	1.294	1.364
3300	1.147	1.297	1.380
3600	1.154	1.302	1.397
3900	1.163	1.304	1.406
4200	1.185	1.307	1.426
4500	1.198	1.311	1.458

Figure 4 shows the effect of time on the wear volume for three different pin specimens. PIN A consistently showed the lowest wear volume throughout the testing period, which reflects the best resistance to material loss due to friction. PIN B showed moderate wear volume, which was higher than PIN A but significantly lower than PIN C, indicating average wear resistance. PIN C showed the highest wear volume at every time interval, with a significant upward trend, especially after 3600 s, reflecting poor wear resistance and the most severe material degradation over time. The graph presents a clear trend where wear volume increases with time for all specimens. However, the degree of wear varies significantly with PIN A performing the best, followed by PIN B, and PIN C showing the highest wear.

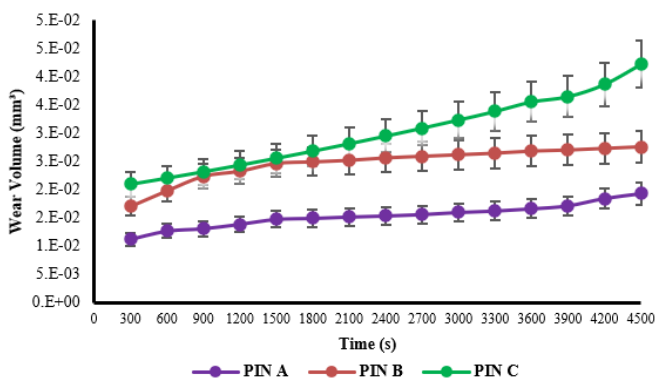


Fig. 4. Relationships between time and wear volumes.

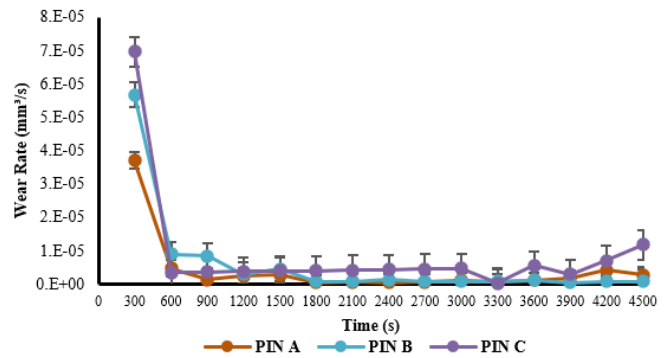


Fig. 5. Graph of the relationship between time and wear rate.

Figure 5 shows the effect of time on wear rate, with all specimens exhibiting relatively high values in the early stage of 300 s, with PIN C having the highest, followed by PIN B, and PIN A with the lowest. After 600 s, the wear rate reduced significantly and stabilized for all specimens. The trend remained relatively constant with minor fluctuations from 900 s onward. PIN A maintained the lowest throughout the test, indicating better resistance to continuous wear. Meanwhile, PIN C generally showed the highest rate, especially towards the end of the test period, indicating more severe material degradation over time. The trend shows that the wear rate was initially high but rapidly decreased as time increased. Among the three specimens, PIN A exhibited the best wear performance, followed by PIN B, while PIN C consistently had the poorest.

Figure 6 shows the effect of the type of PIN on the wear coefficient. PIN A had the lowest wear coefficient at  $8.35189 \times 10^{-7} \text{ mm}^3/\text{N}\cdot\text{m}$  to show the best resistance to wear under frictional forces. PIN B recorded a value of  $1.19481 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$ , indicating average wear resistance. PIN C had the highest value of  $1.82995 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$ , showing the poorest wear performance among the three. The results confirmed that PIN A exhibited superior wear resistance, followed by PIN B, while PIN C was the most susceptible to wear under the same test conditions. Previous studies have also reported wear factors for non-irradiated UHMWPE ranging between  $1$  and  $2 \times 10^{-6} \text{ mm}^3/\text{N}\cdot\text{m}$  [39, 40].

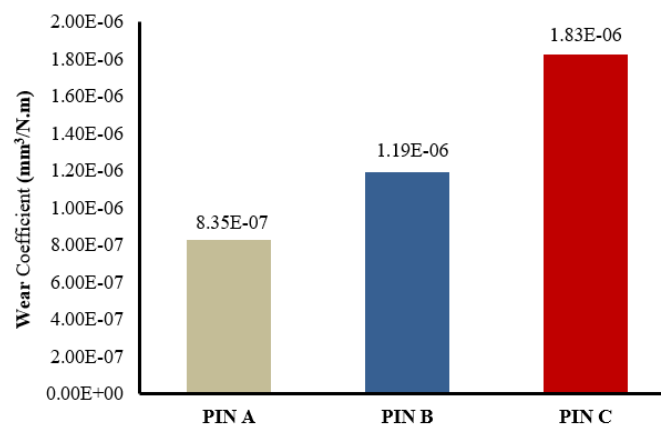


Fig. 6. Wear coefficient of pins.

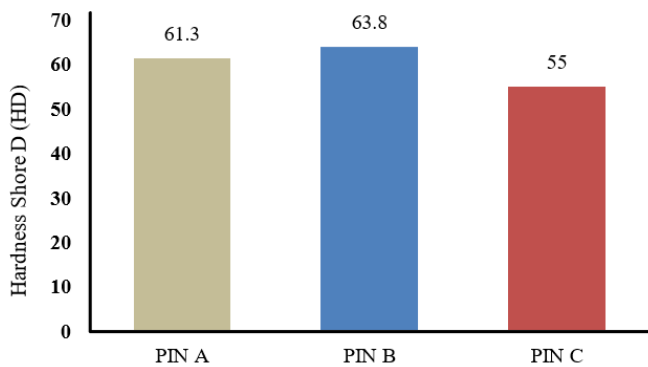


Fig. 7. The hardness of pins.

Figure 7 shows the effect of different PIN types on hardness, measured using the Shore D (HD). PIN B showed the highest hardness value at 63.8 HD, PIN A followed closely with 61.3 HD, and PIN C had the lowest with 55.0 HD. These results show that PIN C was the softest and most susceptible to wear or deformation. This figure indicates that higher hardness generally correlates with better wear resistance, consistent with previous studies. PIN B was the hardest, while PIN C was the least hard, which potentially contributed to its higher wear rate and lower durability during the frictional test.

The microstructure of UHMWPE was observed by SEM at 10,000× magnification (Figure 8). PIN A showed a relatively compact and layered fibrous structure with fewer visible voids or cracks to reflect a more uniform and dense morphology. This structure possibly contributed to the superior wear resistance and mechanical strength. PIN B also had a fibrous and layered structure, but with more pronounced gaps and micro-voids between the layers. This suggests a slightly less compact structure than PIN A, which potentially led to moderate wear resistance. PIN C exhibited a smoother surface with minimal fibrous texture. The absence of a well-defined layered structure could explain the lower hardness and higher wear rate recorded. In general, the SEM images showed that PIN A had the most favorable microstructure to resist wear, followed by PIN B, while the morphology of PIN C was the least resistant to mechanical degradation.

IV. DISCUSSION

The wear track diameter data in Table I and Figure 3 have direct relevance in biomedical engineering with a specific focus on the context of orthopedic implant materials. Wear resistance is a critical property for components such as femoral heads or tibial inserts in joint replacements, where continuous friction in articulating surfaces can lead to particle generation, inflammation, and implant loosening. The smallest wear width suggests the highest resistance to friction-induced degradation. The study in [12] reported that wear performance could be substantially influenced by surface finish, microstructure, and lubrication conditions. Materials with higher hardness and better tribo-chemical stability often exhibit narrower wear tracks under identical friction conditions.

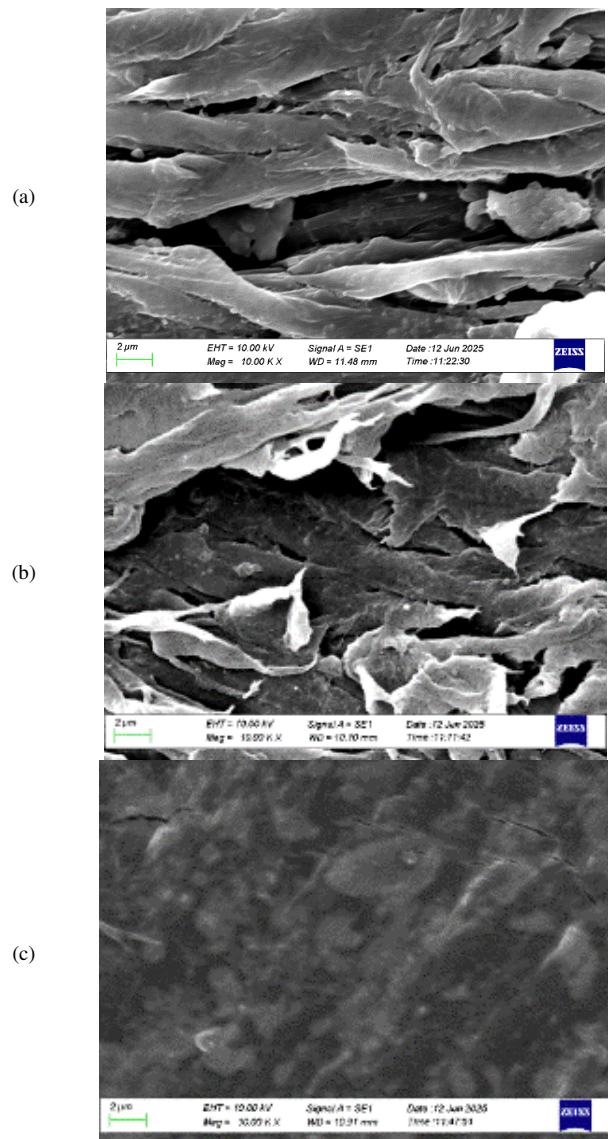


Fig. 8. Microstructure of UHMWPE magnification 10000 times by SEM

The observed visual trend is consistent with the position of Archard’s wear law [38], which states that the wear volume is proportional to the load, and the sliding distance and inversely proportional to the hardness. The observed wear track diameters reflect the physical durability of the materials and are effectively in line with established literature on tribology regarding the correlation between material properties, surface engineering, and wear resistance.

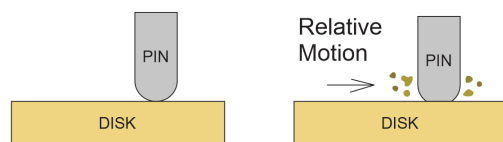


Fig. 9. Adhesive wear mechanism on the pins.

The wear mechanism of the tested PIN specimens can be attributed to adhesive wear during the sliding contact process. Adhesive wear occurs when the asperities from the PIN surface come into direct contact with the counter-face to cause localized bonding and subsequent material transfer or detachment [41, 42]. The dominant wear mechanism in this study was generally adhesive wear (Figure 9), supported by surface deformation and micro-photo observations in Figure 3. The results emphasized that microstructural integrity and hardness were critical factors influencing the wear behavior of UHMWPE-based PIN materials.

Locally manufactured UHMWPE (PIN A) exhibited the lowest wear coefficient of  $8.35 \times 10^{-7} \text{ mm}^3/\text{Nm}$  compared to  $1.19 \times 10^{-6} \text{ mm}^3/\text{Nm}$  and  $1.8 \times 10^{-6} \text{ mm}^3/\text{Nm}$  for PIN B and PIN C, respectively. These values were consistent with the range of  $10^{-7}$  to  $10^{-6} \text{ mm}^3/\text{Nm}$  typically reported in previous studies conducted to test UHMWPE under pin-on-disc or knee simulator conditions [43, 44].

The microstructure observed using SEM provided key insights into the wear performance of UHMWPE used in biomedical applications, specifically for load-bearing implants such as joint prostheses. The compact, fibrous, and layered morphology observed in PIN A was in line with previous studies that correlated microstructural characteristics with enhanced mechanical integrity and wear resistance. According to [45], in biomaterials, a well-organized fibrillar structure in UHMWPE contributed to superior load transfer and resistance to crack initiation, which improved long-term durability *in vivo*. The compact and layered fibrous morphology reflects a highly consolidated polymer matrix with limited porosity and minimal surface defects.

PIN B had a fibrous structure but with more visible interlaminar voids and microcracks, indicating suboptimal polymer consolidation. These features can serve as initiation points for wear and crack propagation, particularly in repetitive or high-contact-load conditions. In UHMWPE, defects are critical due to their function as stress concentrators, which significantly influence mechanical integrity and tribological performance under service conditions [1]. The presence of microcracks is also closely associated with oxidative degradation and chain scission, specifically when the polymer is not adequately stabilized during irradiation or sterilization processes. Moreover, poorly consolidated or partially fused polymer layers can trap oxygen or other impurities to increase degradation and compromise the long-term performance of the UHMWPE material [46].

A comparison with other the pins, with a specific focus on PIN A, which shows a denser, more compact structure, further emphasizes the vulnerability of PIN B. Previous studies consistently showed that uniform consolidation and reduced porosity enhanced the wear resistance of UHMWPE, while fibrous and porous microstructures, as observed in PIN B, exhibited inferior mechanical stability and shorter service life [47]. PIN C had a smoother and more amorphous surface but lacked the defined fibrillar network observed in the other samples. This morphology possibly shows a higher proportion of amorphous phases or lower molecular alignment, which is typically correlated with lower hardness, reduced yield

strength, and increased susceptibility to adhesive wear. Similar inferences were reported in [48], where UHMWPE with less-defined lamellae and reduced crystallinity tended to exhibit higher wear rates, particularly in dry sliding or joint articulation environments.

The Chinese and US UHMWPE products, marked as PIN B and PIN C, respectively, are already commercially available and widely used in orthopedic implant applications. However, the experimental results showed that the locally manufactured UHMWPE (PIN A) exhibited superior wear resistance and favorable microstructural characteristics. This was observed from its consistently better performance in all wear parameters under identical test conditions compared to PIN B and particularly PIN C.

Another interesting observation was that PIN B exhibited the highest hardness value, but its wear resistance was lower than that of PIN A. The trend suggests that hardness is not the only primary determinant of wear performance in UHMWPE. The other properties, such as microstructure, have a more dominant role in resisting material degradation under repeated loading. The superior performance of PIN A, which combines slightly lower hardness with a compact morphology, shows the importance of a balanced relationship between hardness and toughness in achieving optimal tribological behavior for TKA components.

Cross-linked UHMWPE has been widely considered an advanced material for tibial inserts in TKA due to its superior wear resistance compared to conventional products [2, 49, 50]. Meanwhile, metals such as cobalt-chromium and titanium alloys are generally used for the femoral components due to their excellent mechanical strength, toughness, and corrosion resistance [51, 52]. The production and procurement of these advanced biomaterials often require high manufacturing costs and dependence on imports, which can limit accessibility in developing countries. However, conventional UHMWPE and AISI 316L continue to provide a more practical and economical alternative, especially in contexts where cost-effectiveness is an important factor [53]. The adoption of the materials in Indonesia ensures affordability and wider patient access to TKA procedures and also supports the potential development of local manufacturing capabilities. Therefore, this method could reduce reliance on imports and have a positive impact on the national healthcare system and the economy.

## V. CONCLUSION

This study introduced several novel results that could significantly affect the advancement of orthopedic medicine in Indonesia, in particular, and globally in general. The trends identified from the experiments conducted could be concluded as follows:

1. Locally manufactured UHMWPE (PIN A) exhibited superior wear resistance and favorable microstructural characteristics compared to commercially available products from China (PIN B) and the United States (PIN C).

2. PIN A had the smallest wear track diameter, the lowest wear volume, and the lowest wear coefficient, which showed the potential as a reliable material for TKA implants. The microstructure of PIN A, characterized by a compact and layered fibrous structure, contributed to enhanced wear resistance.
3. PIN A could be a promising alternative for orthopedic implant applications, offering improved performance and potentially better patient outcomes.

These three improvements clearly show that previous TKA designs were not developed based on the ergonomic geometry of the Indonesian population. This study contributes substantially to the field by developing a TKA design that accurately reflects the anthropometric and ergonomic anatomical characteristics of Indonesian patients. This achievement provides a strong foundation for future downstream studies, including clinical trials and large-scale fabrication. This is necessary to ensure that the artificial knee joint developed could be applied effectively and benefit patients in need of replacement.

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