Does Femoral Sagittal Plane Curvature, J-Curve, Affect Patellofemoral Performance in Hinge Design?

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INTRODUCTION: The hinge total knee arthroplasty (TKA) is primarily used to address severe knee soft tissue deficiencies. Generic rotating platform (RP) bearing hinge designs provide a flexion-extension (F-E) degree-of-freedom (DOF) at the insert-femur interface, with an internal-external (I-E) DOF at the insert-tray interface. Additionally, in hinge designs, the tibiofemoral (T-F) section of the sagittal femoral curvature-often referred to as a J-curve-comprises a single-radius (SR) segment. Although successful, anterior knee pain and patellofemoral (P-F) complications are among the most common complications in the hinge TKA [1, 2]. The femoral J-Curve has been shown to influence P-F compartment biomechanics in primary and revision TKA [3, 4]. However, the specific effect of a SR J-curve in hinge designs remain poorly understood. Therefore, the primary objectives of this study were twofold: first, to evaluate the influence of SR J-curves on the P-F biomechanics in hinge TKA; and second, to compare the P-F performance of these hinge designs with two commercially available hinges and RP revision TKA constructs.

METHODS: A previously validated forward dynamics model (FDM) was utilized for the analysis (Fig. 1) [4]. The model performs knee biomechanical analysis under physiologically relevant conditions [5]. In this study, analysis was focused on a deep knee bend (DKB) activity, from 5º-120º of flexion. To simulate hinge design, FDM was further modified by locking the femoral anteroposterior (A-P) and mediolateral (M-L) translations relative to the insert, while allowing F-E motion. Additionally, the femur-insert construct was allowed to have I-E DOF on the tibial tray to simulate RP bearing. The collaterals were not modeled to simulate ligament deficiency in hinge designs. Three hinge designs were developed in NX 10.0 (Siemens PLM), each featuring a distinctive SR segment of a J-curve; small SR (S-SR), large SR (L-SR) and optimized SR (O-SR). In each simulation, quadriceps, P-F and patella-tendon forces were reported in the body weight units (1BW=750N). The Grood and Suntay P-F 6-DOF motions were described, with primary focus on the P-F M-L Shift and Tilt. The performance of these SR hinge designs was subsequently compared with two commercially available SR hinge designs (C-Hinge1 and C-Hinge2) and RP revision TKA construct. The A-P and M-L widths, along with the trochlear groove, were identical across the three SR hinges (S-SR, L-SR and O-SR) and RP revision designs. Conversely, the commercially available hinge sizes were chosen to match the closest A-P and M-L widths.

RESULTS: Figure 2 a-c & f summarize the quadriceps, P-F and patella-tendon forces across all simulations. The S-SR and O-SR hinge designs showed peak quadriceps force at mid-flexion, followed by drops of 1.1BW and 0.3BW respectively (Fig. 2-a,f). In contrast, the L-SR, C-Hinge1, C-Hinge2, and RP revision designs experienced continuous increase in quadriceps force with flexion. The relationship between SR value and quadriceps force in hinge designs was most evident between 60º and 100º of flexion. Notably, the peak quadriceps force for O-SR hinge was either smaller or comparable (within 0.3BW) to C-Hinge1 and RP revision design. For P-F force, all designs, except C-Hinge2, experienced peak forces during 75º-80º of flexion, followed by declines ranging within 0.1-3.0BW (Fig. 2-b,f). The influence of the SR value on P-F force was more pronounced in the second half of flexion. Among the three SR designs, the S-SR hinge experienced the highest P-F force (3.4BW), along with the most substantial drop (to 0.6BW). The peak P-F force and later drop for the O-SR hinge was in between those experienced by the S-SR and L-SR designs. Additionally, the peak P-F force for O-SR design was either smaller or comparable (within 0.3BW) to those in the C-Hinge1, C-Hinge2 and RP revision designs. Patella-tendon forces increased with flexion across all, except in S-SR, design (Fig. 2-c,f). The effect of SR value on the patella-tendon force was also more dominant in the later flexion. The peak patella-tendon force for the O-SR design was lower than those experienced by the L-SR, C-Hinge1, C-Hinge2 and RP revision designs. The P-F Shift and Tilt motions followed similar trends for all designs, and varied within 2mm and 2º, respectively (Fig. 2-d,e).

DISCUSSION: The FDM methodology offered unique opportunity to investigate effects of the femoral J-curve on the P-F biomechanics of various hinge designs. All studied hinge designs followed RP philosophy and featured SR segment in their J-curves. The SR values substantially influenced P-F kinetics, especially during the latter half of the flexion, even in the designs with identical A-P, M-L widths and trochlea geometry. However, their impact on the quadriceps, P-F and patella-tendon forces was inconsistent. In design with smaller SR, the peak quadriceps and P-F forces were the highest, yet the peak patella-tendon force was the lowest. Additionally, hinge with smaller SR experienced greater drops in all simulated P-F kinetics during the second half of flexion. These trends highlight the challenge of identifying a unique SR for hinge that would provide optimal P-F kinetic performance. To address this, the revision RP construct was included, as it allows more T-F DOF and is indicated with more soft-tissue presence. The O-SR hinge design used an SR value between S-SR and L-SR, demonstrated that the peak P-F kinetics and P-F kinetic trends during later flexion remain either substantially lower (by up to 2.8 BW) or comparable (within 0.3BW) to those of the commercially available hinge (C-Hinge1, C-Hinge2) and RP revision designs. These findings indicate that the O-SR hinge, with limited T-F DOF and absence of collaterals, can achieve P-F kinetic performance comparable to the more complex revision RP construct, which possesses greater DOF and typically preserves more soft tissue, thereby potentially enhancing hinge patient satisfaction. Nonetheless, more cadaveric and clinical studies are necessary to further confirm these observations. Despite the difference in the P-F kinetics, the femoral J-curve had minimal effect on the P-F Shift and Tilt, likely due to increasing P-F congruency with flexion. In summary, while P-F biomechanics in hinge design can be affected due to varying femoral SR J-curves, an optimal SR value can enable a hinge design to achieve P-F kinetics comparable to that of a RP revision construct.

SIGNIFICANCE/CLINICAL RELEVANCE: The femoral J-curve could significantly influence P-F kinetics in hinge designs, although its impact on different P-F kinetic parameters may vary.

REFERENCES: 1. Varacallo et al.-2024, 2. Justo et al.-2021, 3. Loudon JK-2014, 4. Wachowski et a.-2012, 5. Khasian et al. -2020

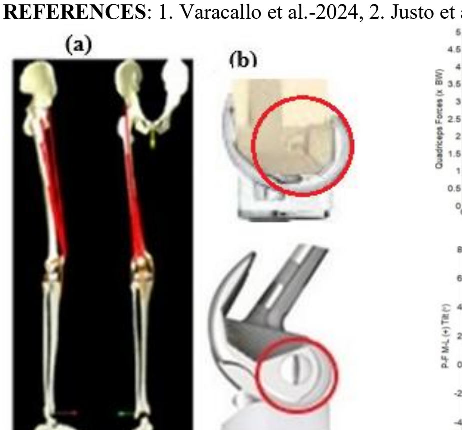
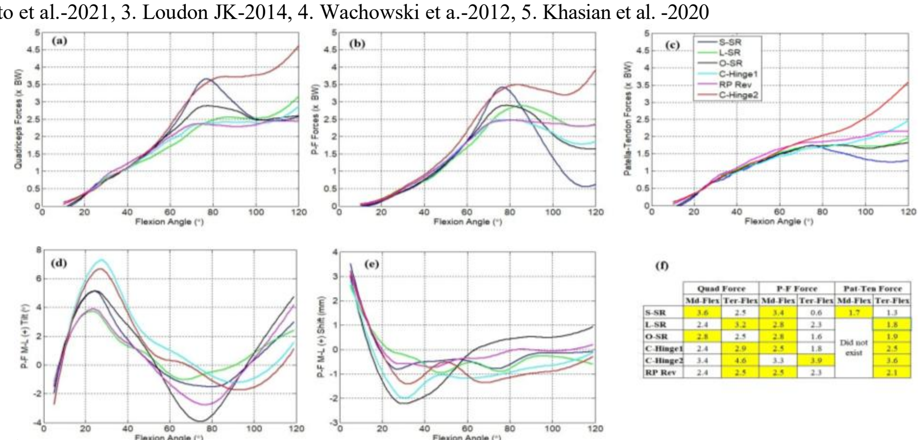


Figure 1: (a) Knee Forward Dynamics Model used to simulate the DKB using the LPS system (b) Two contemporary Hinge designs highlighting different femoral SR J-Curves.



(f)

	Quad Force		P-F Force		Pat-Ten Force	
	Md-Flex	Ter-Flex	Md-Flex	Ter-Flex	Md-Flex	Ter-Flex
S-SR	3.6	2.5	3.4	0.6	1.7	1.3
L-SR	2.4	3.2	2.8	2.3	Did not exist	1.8
O-SR	2.8	2.5	2.8	1.6		1.9
C-Hinge1	2.4	2.9	2.5	1.8		2.5
C-Hinge2	3.4	4.6	3.3	3.9		3.6
RP Rev	2.4	2.5	2.5	2.3		2.1

Figure 2: P-F kinetics for all simulated designs. (a) Quadriceps force, (b) P-F forces, (c) Patella-tendon forces. P-F M-L Tilt (d) and Shift (e) for all simulated designs. (f) Table shows the P-F kinetics at mid-flexion (75º-85º) and terminal flexion (120º). Yellow shades show if the peak forces occurred during mid- or terminal flexion.