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Dynamic response of soft tissue can be disregarded during femoral stem impaction

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ABSTRACT

Background: In cementless total hip arthroplasty stems are inserted into the bone by mallet blows. Surgeons are not instructed to adjust the force of their blows to differences among patients especially with regard to weight. Whether this is linked to complications is yet unknown. This study investigated factors that could affect the mechanical behavior of the femur-tissue system.

Methods: Four cadavers were subject to two total hip arthroplasties by the same surgeon – one side via a lateral approach and the contralateral side via a direct anterior approach. A mass-spring-damper model was used to replicate the mechanical response of the femur-tissue system of the cadavers and make them comparable.

Findings: The mechanical response in terms of mass-spring-damper parameters differed between the approaches (lateral: 16.5 kg, 29.7 N/mm, 467.1 Ns/m; direct anterior: 11.5 kg, 41.7 N/mm, 553.0 Ns/m).

Interpretation: Common metal-on-metal mallet blows in surgery are very short and mostly excite high frequencies that are clearly above the natural frequency of the femur-tissue system. Those overcritical force impulses make the stem slide into the femur before the bone can even start moving. Hence, the individual mechanical behavior of the femur-tissue system can be disregarded provided that the force is applied with very short blows. This needs to be considered for any attempt to replace the mallet in the operation theater (e.g. automated surgical impaction tools) or to modify the mallet (e.g. alternative tip material). Furthermore, it may provide guidance on the fixation of femurs in in vitro testing to mimic surgical reality.

1. Introduction

In cementless total hip arthroplasty (THA), the broaching of the femoral cavity and the implantation of the implant are typically achieved with mallet blows on the broach handle or the stem impactor to drive the broach or the stem into the femoral canal. In every THA surgery, a unique combination of patient-specific body characteristics (e.g. the amount of muscle and fat tissue), the approach to the joint and the patient's positioning on the surgical table need to be addressed. Neither the existing literature nor the manufacturer's surgical instructions provide surgeons with clear recommendations on whether and how to adapt their mallet blows to the diverse scenarios. The sole target for the surgeon is the achievement of the desired implant position without the occurrence of a fracture, seeking to receive sufficient primary stability. As a consequence, number and strength of the mallet blows vary between clinicians (Nassutt et al., 2006; Reynolds et al., 2024; Scholl et al., 2016). In recent years, automated surgical impaction tools have been introduced (e.g. IMT's Woodpecker, Johnson & Johnson MedTech's Kincise, Zimmer Biomet's Hammr) and are currently gaining popularity in the operation theater (Thalody et al., 2023). One of their key advantages is the high reproducibility of blows, which aims for less variability in the fixation process (Konow et al., 2022) and is a step towards more standardization in the operating room. Additionally, the automated surgical impaction tools reduce the physical load for surgeons

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during the impaction process, allowing them to work more efficiently and reduce fatigue related failures during surgery (Ferrari et al., 2021). The patients, however, cannot be standardized and their inter-individual variability remains. Insufficient primary stability and periprosthetic fractures are still major reasons for THA-revisions (National Joint Registry, 2023; Australian Orthopaedic Association National Joint Replacement Registry, 2024; Grimberg et al., 2024). It is conceivable that both could potentially be associated with an inadequate consideration of the flexible connection of the bone to the surrounding soft tissue as well as the positioning and fixation on the table. To enable a comparison of different bone-tissue systems, their mechanical response can be described with a fundamental phenomenological model based on a mass-spring-damper system (Doyle et al., 2019). Therefore, the aim of this study was to investigate different femur-tissue systems with varying influencing factors (e.g. BMI, surgical approach and patient positioning) to gain insights into the order of magnitude and variation of the system parameters.

2. Methods

2.1. Cadaveric measurements

Four fresh human cadavers without any fixation were included in this study and stored at 4 °C prior to measurements. Their personal information was anonymized for the complete study. The only accessible data were age at death, sex, weight and height (35 to 65 years; male/female = 3/1; 70.4 kg to 117.6 kg; 1.81 m to 1.84 m). The Ethics Commission of the Medical Association Hamburg had approved this post mortem cadaveric study (2024-300436-WF).

The cadavers were treated alike patients in THA surgery by an experienced surgeon. For the lateral approach (LA) on one side, the cadavers were placed in lateral position on the autopsy table (ST HS 11–02, UFSK, Regensburg, DE) and stabilized with a standard tunnel pad and a pair of lateral hip positioners. On the contralateral side, a direct anterior approach (DAA) was performed in supine position. For the sake of consistency, ropes were used to hold the retractors and the knee in place. The padding in lateral position, the incision, the access to the joint and the osteotomy of the femoral neck were performed in accordance with the established procedures for THA surgery.

Axial excitation of the femur (sinusoidal, increasing frequency 0.5 Hz to 1000 Hz, 60 s) was applied by an electrodynamic shaker (TV 51075-M, TIRA, Schalkau, DE). This shaker (Fig. 1) was attached to a metal plasterboard dowel (GKM, Fischer, Waldachtal, DE) that was screwed into the proximal femur prior to broaching and secured with bone cement (Palacos® R, Heraeus, Wehrheim, DE). The shaker itself was suspended from a gallows and additionally supported at the rear to prevent uncontrollable resonance. The applied uniaxial force was measured at the tip of the shaker (9321C, Kistler, Winterthur, CH). The resulting accelerations were measured with an accelerometer that was screwed to the anterior cortex of the proximal femur close to the resection line of the neck cut (triaxial; M354C02, PCB Piezotronics, Depew, NY). Data acquisition was performed at 500 kHz (NI-9222, National Instruments, Austin, TX). The excitations were repeated three times for all cadavers and both approaches ($n = 24$). Laserscans of the field of surgery (HandySCAN BLACK™ Elite Limited, Creaform, Lévis, Quebec, CA) were used to establish a femur based Cartesian coordinate system: z in axis with the positive direction of force along the femoral axis, x parallel to the surface of the table, y perpendicular to x and z. The measured triaxial accelerations were later transformed in this coordinate system.

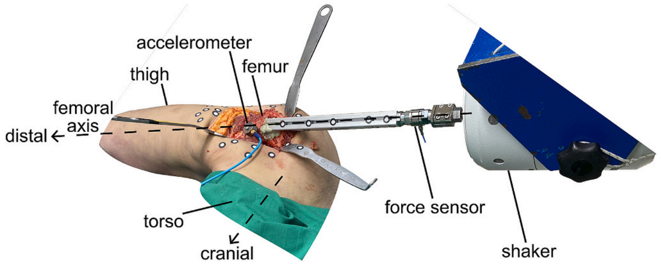

Fig. 1. Shaker mounted to the proximal femur during a lateral approach.

2.2. Data evaluation

The frequency response function (FRF) was described in terms of accelerance, which is calculated as the ratio of acceleration to force in the frequency domain (Ewins, 2000). The repeatability of consecutive measurements was evaluated with the mean coefficient of variation (mCV) defined as the ratio of variance to mean averaged over all frequencies.

A phenomenological model of two combined single degree of freedom mass-spring-damper systems in series was fitted to the experimental data to derive a parameter based description of the mechanical response (Fig. 2; Doyle et al., 2019; Schlieker et al., 2024b). One represented the oscillation of the femur in the surrounding tissue (femur-tissue system), whereas the other one covered the low-frequency vibrations resulting from the environment as the table fixation of the cadaver (support system). The six resulting model parameters were determined for each cadaver and each approach by optimizing the mean absolute percentage error (MAPE) between the simulated and the measured accelerance between 1 Hz and 25 Hz (fmincon, Matlab 2024A, MathWorks, Natick, MA; Simscape, Simulink 2024A, MathWorks). Higher low energy frequencies above that range couldn't be described by the two mass-spring-damper systems and did not lie within the scope of this study. Although the identical table was used for all measurements, the parameters of the support system were redetermined for each cadaver and each approach, as the cadaver's weight, the table's height and the direction of the excitation differed.

2.3. Statistical analysis

The statistical analysis was performed with a type I error level of $\alpha = 0.05$ (SPSS 26.0, IBM, Armonk, NY). Given the rarity of cadaver studies, the group size was small. To account for this, p-values between α and 0.2 were considered as trends. Normality was checked with the Shapiro-Wilk test and homogeneity of variance with the Levene's test. Pearson correlations were performed for correlation analysis. Based on the assumption that the mechanical situation on both sides of each cadaver is similar, a dependent t-test was used to compare the two approaches.

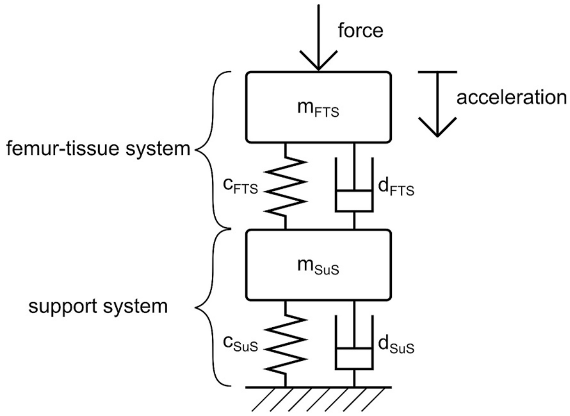

Fig. 2. Phenomenological model of the setup represented by two combined single degree of freedom mass-spring-damper systems in series. The force was applied to the femur-tissue system (FTS) that was linked to the support system (SuS).

3. Results

The mCV of the measured FRF between 1 Hz and 100 Hz ranged from 0.8 % to 2.5 %. This small variation allowed combining consecutive measurements for each approach on each cadaver by averaging the FRF.

The MAPE of the simulated FRFs ranged from 3.2 % to 4.4 % for the DAA and from 2.3 % to 3.9 % for the LA, respectively (Fig. 3). Above 25 Hz the measured and the modelled accelerance diverged. In accordance with this, the phase shift of the measured accelerance did not reach 0° as the simulated did.

Dynamic properties tend to increase with increasing body weight for the LA (mass: $R^2 = 0.875$, $P = 0.065$; stiffness: $R^2 = 0.870$, $P = 0.067$; damping: $R^2 = 0.857$, $P = 0.074$; natural frequency: $R^2 = 0.847$, $P = 0.080$; Fig. 4A-D). For the DAA, only the damping followed a similar trend ($R^2 = 0.797$, $P = 0.107$), while the effective mass was found to be nearly constant ($R^2 = 0.030$, $P = 0.827$). Slight increase in stiffness and natural frequency for the DAA was not significantly related to body weight (stiffness: $R^2 = 0.474$, $P = 0.312$; natural frequency: $R^2 = 0.363$, $P = 0.397$).

The effective mass of the femur-tissue system was determined as 11.5 kg (SD 0.54 kg) for the DAA and 16.5 kg (SD 1.13 kg) for the LA, respectively ($P = 0.004$). In contrast, the DAA resulted in a 12.0 N/mm higher stiffness (41.7 N/mm, SD 6.2 N/mm vs. 29.7 N/mm, SD 6.4 N/mm, $P = 0.010$), and consequently, the natural frequency was on average 2.9 Hz larger for the DAA than for the LA (9.6 Hz, SD 0.9 Hz vs. 6.7 Hz, SD 0.5 Hz, $P = 0.003$). The difference in damping was only a trend and again the DAA resulted in higher values than the LA (553.0 Ns/m, SD 184.6 Ns/m 467.1 Ns/m, SD 177.3 Ns/m, $P = 0.146$).

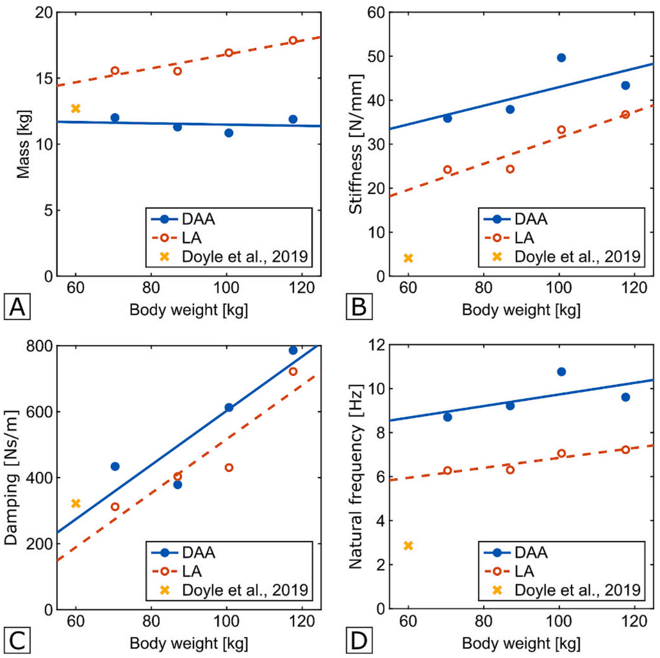

Fig. 4. A) mass, B) stiffness, C) damping, and D) natural frequency of the femur-tissue system for the direct anterior approach and the lateral approach in dependency of the cadaver's body weight. The single data from Doyle et al. (2019) was included for visual comparison.

4. Discussion

The repeatability of the consecutive measurements was high. The low mCV of the measured accelerance was caused by the excitation of the shaker and proved that three repetitions per cadaver were sufficient to effectively capture the system's dynamics. Based on the MAPEs of the simulated FRFs it was shown, that in accordance with Doyle et al. (2019) the usage of a mass-spring-damper system was a sufficient approach to simulate the dynamic response of the femur-tissue system – even though it had to be expanded by a component representing the support in this study.

The effective masses for both approaches were higher than the weight of a plain femur showing that not only the femur was excited, but also a part of the surrounding soft tissue and the limb. This was also visually observed during the measurements. The independence of the effective mass from the body weight for the DAA was found to be counterintuitive, particularly when there was a clear trend for the LA. However, the approaches differ in the amount of support, which can explain the different parameters of the femur-tissue system.

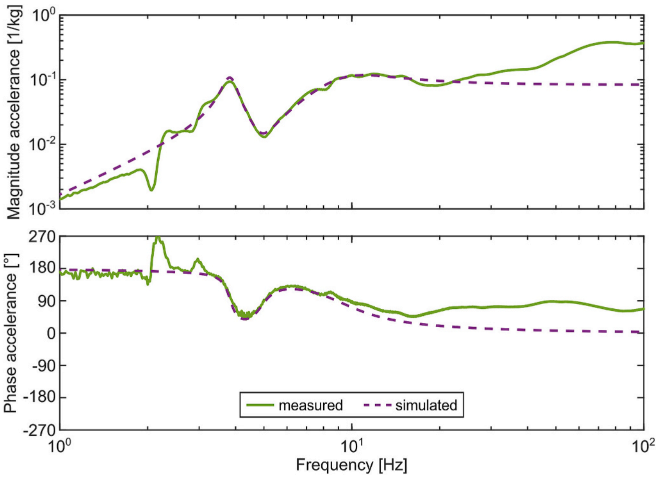

Fig. 3. Exemplary Bode diagram of a measured and the corresponding simulated frequency response function (mean absolute percentage error = 3.2 %). The first peak in magnitude and the corresponding phase shift, both at 4 Hz, indicate the natural frequency of the support system. The femur-tissue system is a heavily damped system, which leads to the diminished intensity of the rather flat peak at approximately 9 Hz.

The effective masses and damping characteristics resemble the single value in the literature (Doyle et al., 2019). However, the stiffnesses are six to twelve times higher than in the literature, resulting in natural frequencies that are 2.4 to 3.5 times higher. One potential explanation for this could be that their cadavers were embalmed using phenol in addition to being cooled (Doyle et al., 2019), whereas the decedents used in the present study stayed unfixed. Phenol has the capacity to either decrease the tissue stiffness by denaturing protein or increase it by dehydrating the tissue (Richins et al., 1963). The extent to which these two effects occur cannot be assessed at this point. However, it is important to note that a common side effect of embalming techniques is the alteration of tissue properties (Galbusera et al., 2018; Holewijn et al., 2017). Without fixation, the cadavers for the present study had to be relatively fresh. As a consequence, rigor mortis had to be broken by mobilization prior to the surgical procedure, but did not re-establish during the subsequent examination. However, parts of the muscles may still have been hardened. Additionally, although a similar positioning was used, different muscle releases for the LA as for the posterior approach used by (Doyle et al., 2019) are needed. Furthermore, the anatomical subjects in the present study were younger (35–65 years vs. 81–94 years) which might come along with higher stiffness of the soft tissue.

Both studies used cooled cadavers and the reduced body temperature could have led to an overestimation of the tissue stiffness in comparison to living patients (Krompecher, 1981). Due to the additional damage to the bone, extended operating time and increased risk of infection, in vivo studies are not ethically justifiable. Therefore, human cadavers are the best available substitute model to gain better knowledge of the mechanics of the femur-tissue system.

In the present study, a shaker was used to excite a broad range of harmonic frequencies with a reasonable amount of energy to receive a complete transfer function. In contrast, mallet blows are commonly used in clinical practice to drive broaches or implants into the bone. These blows cause a short non-harmonic force excitation, which can be approximated as superposition of sinusoidal half-waves (Fourier transform) with durations of approximately 0.15 ms to 0.3 ms (Albini Lomami et al., 2020; Dubory et al., 2020; Elias et al., 2000; Glismann et al., 2024; Schlieker et al., 2024b). Transferred in the frequency domain this means that predominantly frequencies in the single-digit kHz range are excited. This excitation is orders of magnitude above the natural frequencies of the different femur-tissue systems and the excitation can be regarded as overcritical. The consequence of the overcritical excitation is that the accelerated stem or broach slides into the femur before the bone even starts moving (Bishop et al., 2022). Thus, with respect to the implantation dynamics, differences in the femur-tissue system or the support system (with its even lower natural frequency) can be disregarded (Krull et al., 2017; Schlieker et al., 2024b). The same is applicable for the assembly of implant components (Doyle et al., 2019). The excitation during broaching might be slightly different due to longer force transmission during plastic deformation. Little relevance with regard to the natural frequency of the femur-tissue system is expected.

Excitations below the natural frequency of the femur-tissue system or even quasi statically with its easy to control peak forces would require additional fixation of the femur. Without fixation, they would lead to soft tissue damage, since the femur would be pushed distally without proper seating of the stem. Even though blows from hand-operated mallets bear some variability (Nassutt et al., 2006; Reynolds et al., 2024; Scholl et al., 2016), their blows are overcritical and lead to a sufficient result. Softer mallets (e.g. polymer or copper) lead to longer blows (Bishop et al., 2021). In extreme cases this could result in an excitation of lower frequencies and consequently could interfere with the femur-tissue system. Hence, the energy would be absorbed by the surrounding tissue instead of being used for the seating of the implant. This is also applicable for automated surgical impaction tools – as long as their blows are short enough and lead to an overcritical excitation, they can be a viable alternative to hand-operated mallets. It is important to note that the excited frequencies are not equal to the repetition rate of blows (e.g. IMT's Woodpecker: 70 blows per second (Goossens et al., 2017), Johnson & Johnson MedTech's Kincise: 6 blows per second (Konow et al., 2022), Zimmer Biomet's Hammr: 6 blows per second (Zimmer Zimmer Biomet, 2024)). The devices apply very short impulses followed by longer interruptions and no harmonic excitation.

In addition to their clinical application, these findings can also be applied to the testing of implants and surgical instruments. In many in vitro studies excised femora without soft tissue are fixated relatively rigidly. It is therefore likely that in these cases the system stiffness exceeds that of the in situ situation. As a consequence, the results might only be transferred to the clinical situation to a limited extent.

The findings of this study are subject to a few limitations. The incision had to be slightly longer than usual for a standard primary THA surgery to be able to attach the shaker and the accelerometer to the proximal femur. This resulted in the necessity for the release of additional soft tissue, which could have affected the tissue stiffness in comparison to the actual surgical situation.

The measurement of the mechanical response and the numerical approach are predicated on the assumption that the femur-tissue system exhibits linear behavior. An impulse mallet could have been used to apply a force in the correct order of magnitude, but low frequencies would insufficiently be excited and thereby the determination of the natural frequency of the femur-tissue system would not be possible (Schlieker et al., 2024a).

Autopsy tables or surgical tables differ, but are likely to influence the measurements in a characteristic and itself comparable way. In this study, the movement of the table could be clearly isolated in the data, since the support system had a lower natural frequency than the femur-tissue system and did therefore not affect the determination of the dynamic properties of the latter.

5. Conclusion

The findings indicate that the dynamic properties of the femur-tissue system possess a natural frequency, which is orders of magnitude below the frequencies that are excited by the force impulses experienced during femoral stem impaction with mallet blows. As long as implantations are performed with such short impulses, the force input remains overcritical, and consequently, the femur-tissue system and the support system (e.g. amount of soft tissue, fixation, positioning or surgical table) does not have a relevant influence on the dynamics of the femoral stem impaction. The surgical procedure during impaction of an implant therefore does not have to be adapted to specific patient characteristics or approaches as long as short metal-on-metal blows are applied. This is not necessarily the case when the instruments' materials or the impaction philosophies are altered.

CRediT authorship contribution statement

Peter J. Schlieker: Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Frank Lampe:** Writing – review & editing, Investigation. **Johann Zwirner:** Writing – review & editing, Investigation. **Benjamin Ondruschka:** Writing – review & editing, Supervision, Resources. **Michael M. Morlock:** Writing – review & editing, Supervision, Resources, Funding acquisition. **Gerd Huber:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

MMM reports financial support was provided by Johnson & Johnson MedTech. FL reports a relationship with Johnson & Johnson MedTech that includes: consulting or advisory. FL reports a relationship with Aesculap AG that includes: consulting or advisory. MMM reports a relationship with Johnson & Johnson MedTech that includes: consulting or advisory, funding grants, and speaking and lecture fees. MMM reports a relationship with CeramTec GmbH that includes: funding grants and speaking and lecture fees. MMM reports a relationship with Peter Brehm GmbH that includes: funding grants. MMM reports a relationship with Mathys Enovis that includes: speaking and lecture fees. BO is member of the board of the German Society of Legal Medicine; GH is member of the board of the German Society of Biomechanics.

If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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