Towards a better understanding of the need for better joint force monitoring when balancing knee joint force during Total Knee Replacements

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Abstract

Osteoarthritis (OA) is the most common joint disease affecting 18% of women and 10% of men over 60 (Glyn-Jones et al. 2015). OA causes articular cartilage in the joint to wear in excess either by, old age, trauma, mechanical wear, or obesity which results in abnormal regrowth of the bone, causing swelling, pain, and reduced mobility of the joint (Filippiadis et al. 2019; Fransen et al. 2015). If OA occurs in the knee, it can reduce a person's ability to walk on leveled ground and up stairs, reducing the amount of work and daily tasks one can perform, which is a major disability (AAOS 2020). For this reason, a partial or total knee replacement (TKR) is often implemented by removing the affected area and replacing the damaged areas with a metal and polymer prosthesis (Azar et al. 2020). One important element in any joint operation is the adjustment or presetting of the initial tension or forces holding the joint in position. Currently, there is no ideal tension or load intensities to target. Sufficient initial tension is vital to prevent dislocation. Excess tension causes overload or stress in the joint resulting in higher stress during ambulation that can also cause joint failure. Correct initial tension and alignment ensure correct kinematics as well a normal range of motion. Some joints have single hemispherical contact surfaces such as the shoulder or hip and some have multiple contact surfaces. Surgeons speculate the importance of accurate joint force measurement during joint operation and discuss various force measurement techniques such as the use of robotic manipulating arms, force plates, or dedicated force transducers. These forces are important as they control outcomes such as symmetry or range of motion. In this paper, the nature of the forces through the knee during gait analysis was investigated. Measuring force using a force plate, and interpolating it, to force through the knee is different from measuring forces in the joint during operation. The latter needs dedicated smart transducers. The relative merit is discussed as well as how these two can inform each other.

1. Background

A TKR or total knee arthroplasty (TKA), is a surgical operation where the knee joint is completely replaced with a combination of metal and polymer components (NHS 2019). The procedure is quite common where over 100 thousand TKR surgeries took place in 2017 in the United Kingdom (UK) with numbers growing every year (Evans et al. 2019). Shortly after the operation is complete the patient can experience pain, discomfort, and stiffness (Sheil 2019). Physiotherapy is usually performed to help the patient maximize the recovery rate of the knee and ensure no further damage is caused due to the ill-prepared joint. Overall, it can take up to a year for the knee to be as strong and resilient as it can be (AAHKS 2020). The patient will have to reduce the amount of aggressive sport and physical action on the knee after the operation is complete. This is due to the fragile nature of the knee and to reduce wear of the prosthesis (NHS 2019); (Sheil 2019).

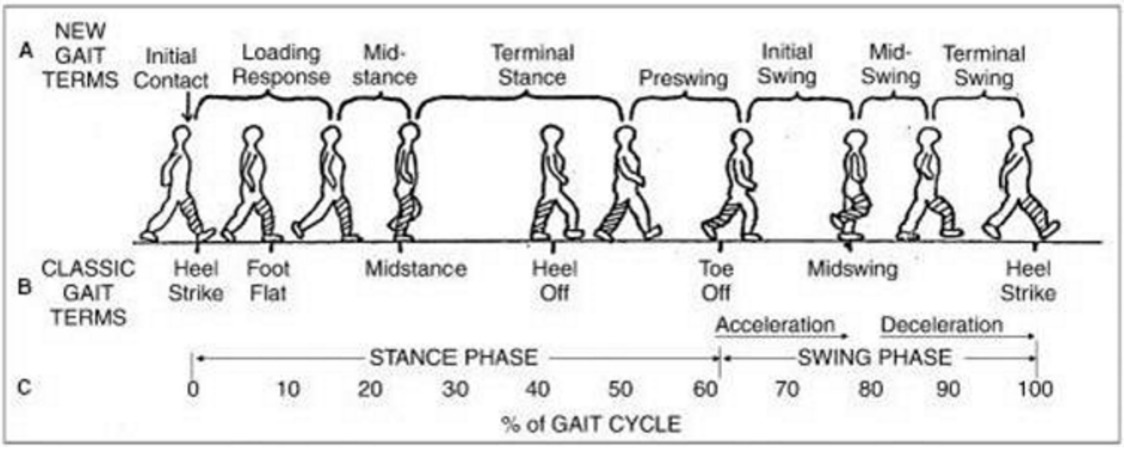

Figure 1: Walking Gait Cycle with the 8 phases of a step and key events noted at the relevant percentage of the gait cycle (Kardasheh 2016)

The effectiveness of TKR operations is usually considered high (Azar et al. 2020) using gait analysis. Although literature may suggest the abundance of high-quality results is due to patients positively responding to initial questioning from medical staff. However, when these same patients were questioned more privately and in-depth, they admitted to continued pain and immobility months after the operation (Woolhead et al. 2005); (Mandeville et al. 20017). A study by Mandeville (2007) was performed on 15 female and 6 male subjects with a mean age of 63.7 years old 6 months after a TKR operation, the study supports this idea of reduced quality of final TKR outcome where patients still showed reduced velocities and reduced knee flexion when compared to the control. Dieppe (1999) indicates that the traditional methods of reviewing the success of prosthesis are based on the duration of time to prosthesis failure.

Although, it appears modern determinations of TKR success are more stringent with the National Joint Registry finding implant survivorship to be an insufficient measure of satisfaction (NJR 2020). A study by Bigg (2019) using 3D video capturing technology in conjunction with 2 force plates recorded the kinematics and kinetics of pre- and post-TKR patients which found that objective gait biomechanics, such as kinematic and kinetic results showed strong correlations to the patient-reported outcomes which were measured using the Oxford Knee Score and Knee Outcome Survey. Due to such a high number of these operations being performed every year it is thought that a more objective study of the key kinematics and kinetics generated by the patient's lower extremities can provide a clearer objective insight into the cause of gait variations. Furthermore, there appears to be no mention of joint interfacial forces other than the overall force measure externally using a force plate. These load intensities and their consequences multiply during running, increasing the need for further study or understanding of the link between kinematics and kinetics and more detailed load measurement.

The failure of a knee replacement surgery is evident due to resultant pain, discomfort, or loss of function that often requires a revision surgery which is costly and carries an inherent risk of further complication due to the inadequate understanding/knowledge of the joint force mechanism at the joint interface. The lack of detailed understanding still exists today. Revision knee surgery is complex and expensive and there is no guarantee of any improvement due to the additional risk of further complications.

2. Development of the TKR force monitoring and measurement process.

TKR success is measured using gait analysis and by then it is usually too late. To get it the right first time the exact knowledge of the joint forces and their tracks over the joint surface is vital to ensure symmetry. The joint assessment is usually passive and assessed in an artisan fashion using surgeons' experience which can be subjective at best. Also, the joint kinematics change because of the implant shapes and forces in soft tissues. In practice, a passive test to measure the range of motion under identical forces and moments between the operated and unoperated leg may be a good indicator of the similarity in joint forces between the normal and the TKR knee. This is not a common practice. Single joint force balancing using modern transducers is gaining momentum making them more vital during TKR. However, there are not many in the market and their validity and integrity are a question for the investigator as it is difficult to isolate the total force, and tracking contact force over the entire joint surface is subjective, limited, and not fully investigated - in the author’s opinion.

Study of terminology

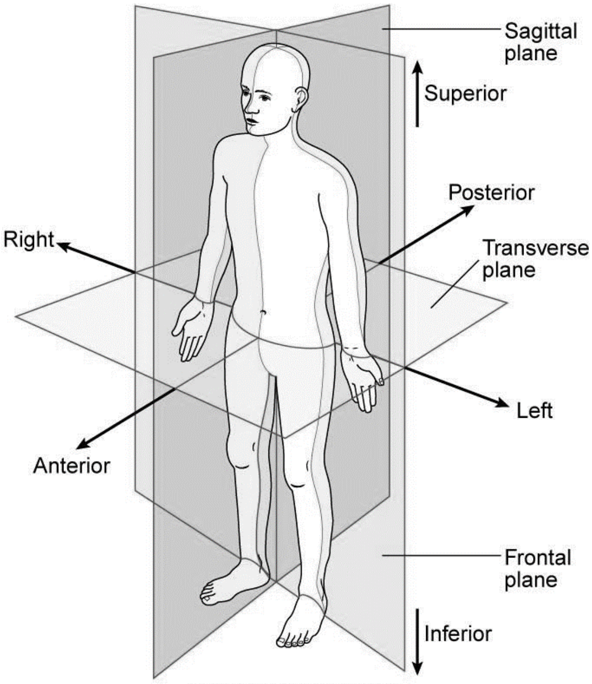

Figure 2: The Three anatomical planes of the human body with the names of both sides of the planes. (Bennet 2020)

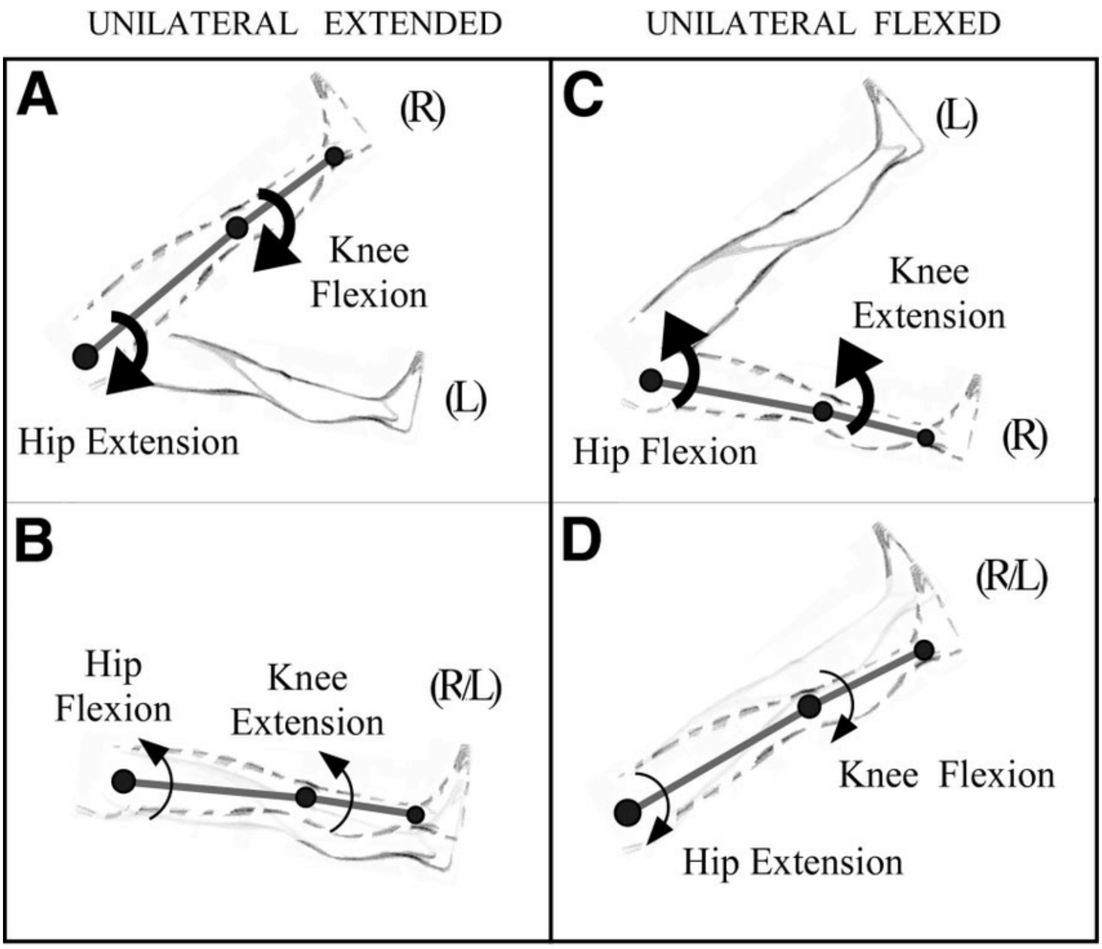

Figure 3: Diagrams of hip and knee movements that show the name given to the direction of movement. (Onushko and Schmit 2007)

A feature of gait analysis is the three planes of view of the subject in an upright position, these being the sagittal (side), coronal (front), and transverse planes (top) (Figure 2). Another key set of nomenclature is the descriptors of muscle behavior and consequent movements in the lower body (Figure 3) (Whittle 2014). Most studies and literature use the sagittal plane as the plane of focus. Sadeghi (2003) reasons the focus of this plane due to most activities occurring in the sagittal plane.

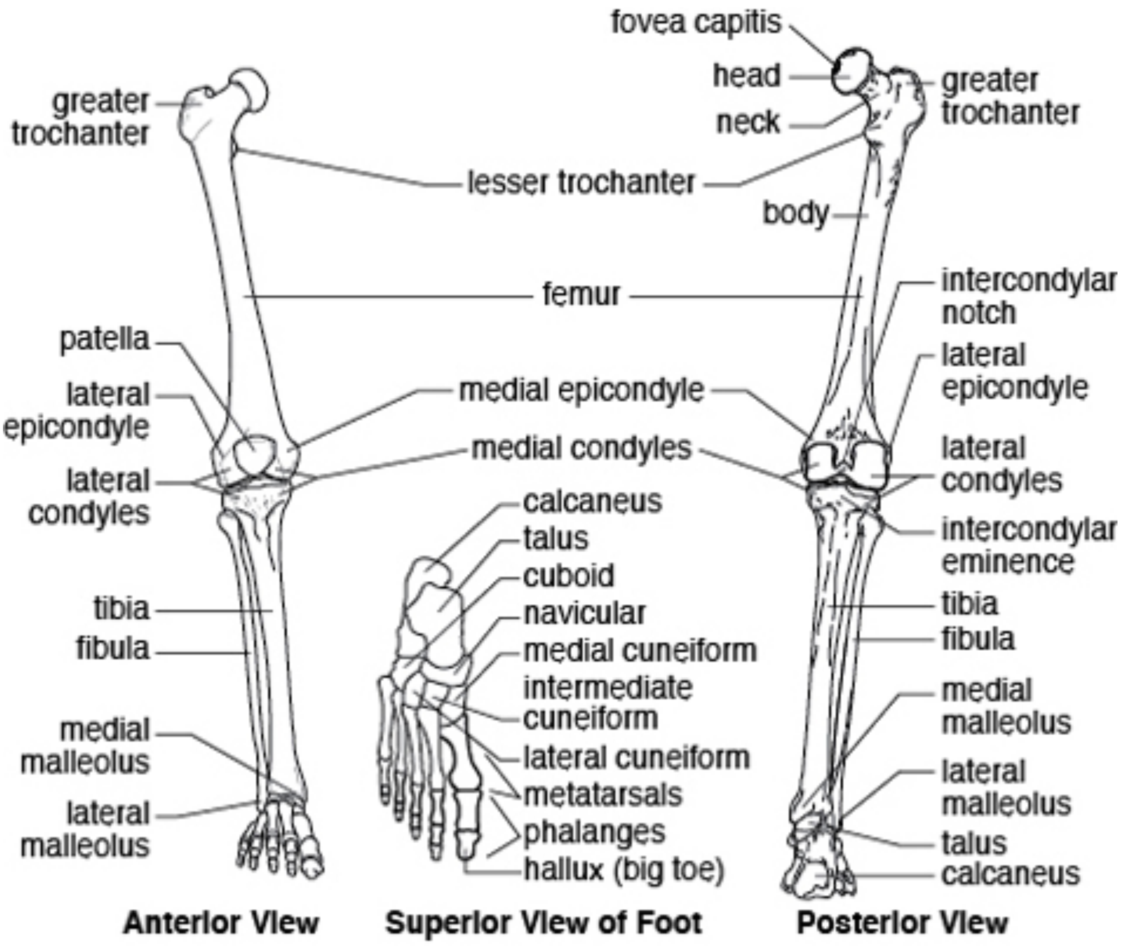

Figure 4: Annotated picture of the bones below the pelvis and the relative names for each bone. (Shaba 2015)

Figure 4 gives the name and location of the major bones situated between the lower end of the spine and above the ankle joint. The three main bones affected directly by the TKR surgery are the tibia, femur, and patella.

Running and walking gait, currently used to assess the outcome of TKR, share some basic kinematics and dynamics characteristics but there are key differences, these being the increased velocity and the reduction or a complete absence of a dual support phase. The greater forces are due to the transference of load i.e., at the beginning and end of the stance phase (Cappellini et al. 2006; Sheila et al. 2005). An example of the increase of force can be demonstrated from the maximum ground reaction force of 1.3 and 2.8 times greater than body weight at the toe-off event when walking and running respectively (Sheila et al. 2005). As well as the changes to forces being exerted on the body when running, the joints also display larger kinematic extremes in the sagittal plane with there being a notable joint excursion. Both the hips and knees have enlarged flexion, alongside greater dorsiflexion and plantar flexion in the ankle (Mann and Hagy 1980; Sheila et al. 2005). Therefore, fast runners require much greater flexibility to handle the increase in range of motion (Sheila et al. 2005).

Material Technology

There are many manufacturers of TKR knees. The type and detail of individual knee systems can be sourced from the manufacturers. However, they all have the same common features and dedicated tools for their implementation. Looking at the published materials, they all seem to be working well and with similar or comparable outcomes/success rates. This is true when normalizing all the data. However, the need for revision surgery still exists and numbers are quite significant according to NJR. The joint failure can be attributed to multiple factors. One of them being inadequate or excess joint interfacial forces. Another one is the lack of knowledge of exact or ideal values of initial contact force or tension and the path of contact point tracks on the joint surface during various walking or running conditions. The surgeon's experience varies with different knees and that may also be a significant or contributing factor. A common transducer that allows for the proper measurement and balancing of the joint force during surgery will help to eliminate some of the contributing factors in knee failure.

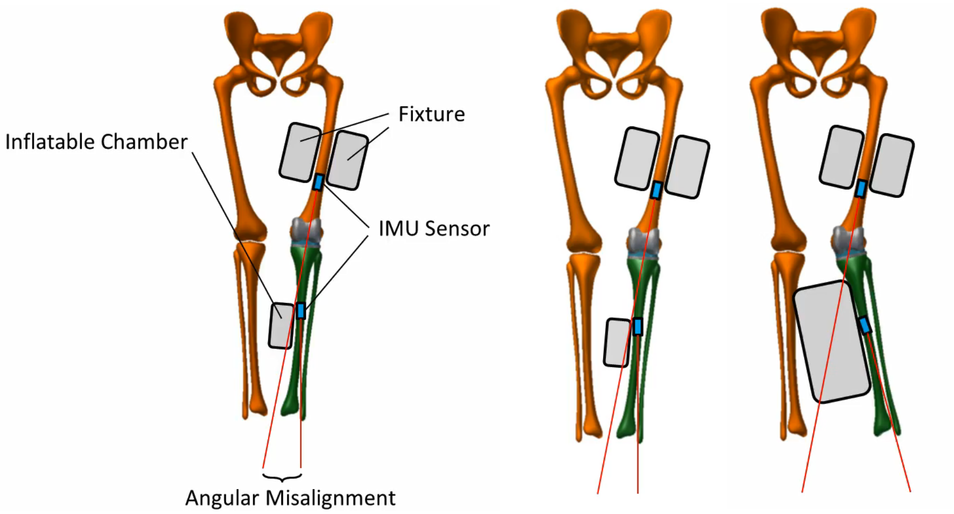

Figure 5: Tool for alignment

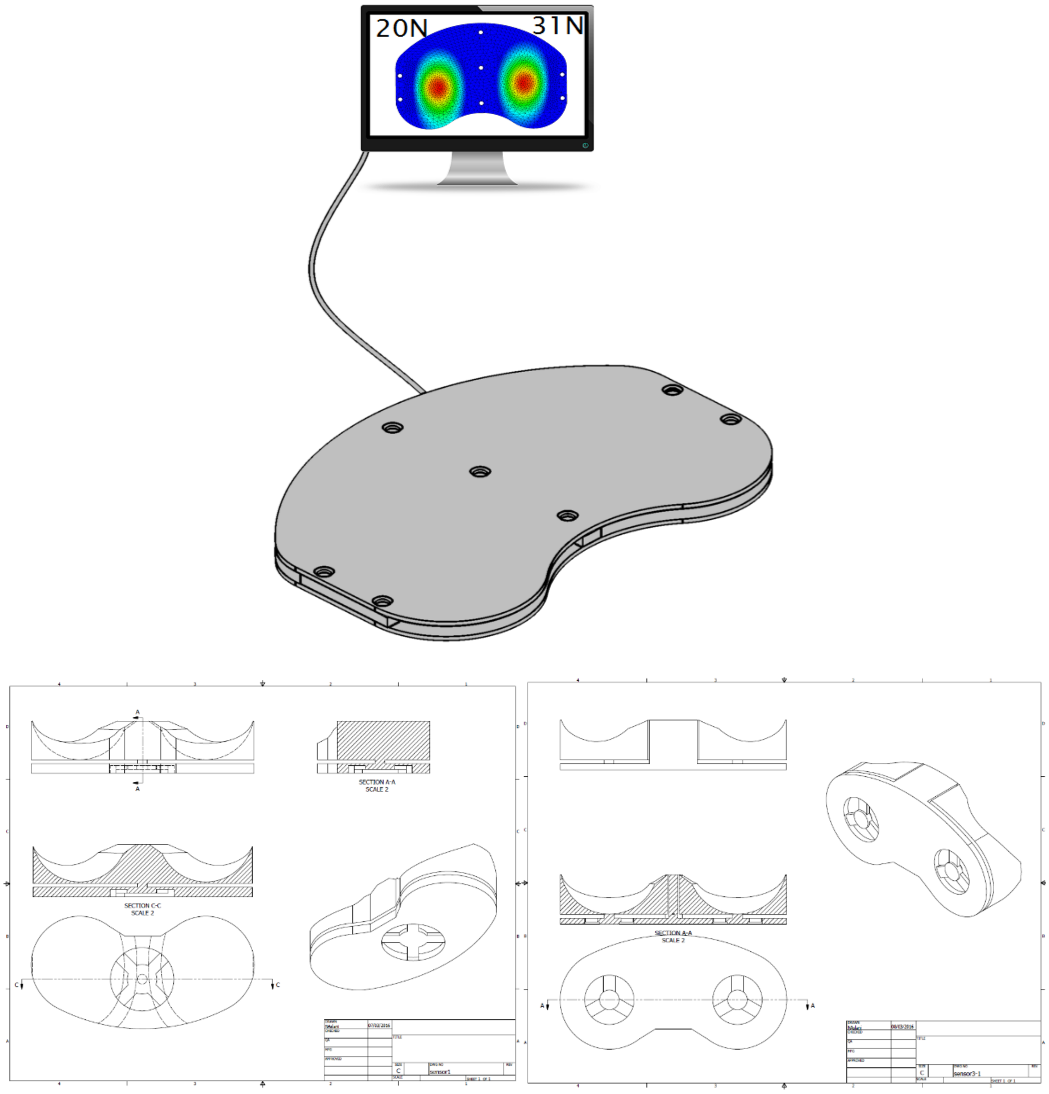

Figure 6: Load transducer

Technology can assess and track the force on the implant. That, combined with a passive adaptive load assessment system, will be able to passively compare and set the joint force to match that of the normal non-operated joint, matching the initial condition of the operated joint to that of the non-operated joint in a passive mode.

Alignment, balancing

Alignment of joint during surgery plus exact measurement of compartmental forces during a TKR plays a major role in the outcome of a surgery. Passive movement of the joint during a TKR is significantly different between left and right in terms of contact forces involved. However, tracking the forces and monitoring their magnitude during an operation using a calibrated input force or moment can inform the surgeon about the ideal passive joint force or tension that needs to be achieved. This can result from introducing a smart passive joint force transducer. There is some significant new technology being introduced for alignment using optics/lasers. CAS or computer-aided surgery is relatively new. Robotics surgery has significantly improved the alignment process as well as the accuracy of placement and cuts but adds some risks. A Robotic arm can apply constant or measured forces and displacement. This is a measure of action or the overall forces involved. It cannot monitor or track the load intensity and contact point kinematics which can also be quite significant if symmetry in gait for both running and walking is a target/goal.

The use of a transducer to monitor in-service load in the knee during operation offers significant insight into what is happening in the knee joint. This combined with known input force and input moment, can assess and compare a passive range of motion between the left and right knee during TKR while the joint is in a passive state. This can also be used to monitor and measure the compartmental forces in the knee joint. A new generation of sensors such as e-Libra (Zimmer Biomet) or Verasense (Stryker) can measure and track the contact points and should significantly help to better balance the knee.

Figure 7: eLibra and Verasense (Verasense 2016 and eLibra)

Above are two of the current/existing tools with abilities for surface tracking ability or compartmental force balancing and it seems that there is still room for further improvement.

3. Discussion

In this paper, the result of gait analysis for 12 TKRs and 12 health controls are presented for reference to show that overall TKRs work when looking at normalized data within the population. In this study, the effects of force and moments passing through the knee were concentrated on. Gait data was generated for both walking and running during the kinematic study of the joints and reflects on their variation concerning the forces and moments passing through or about these joints.

Knee walking

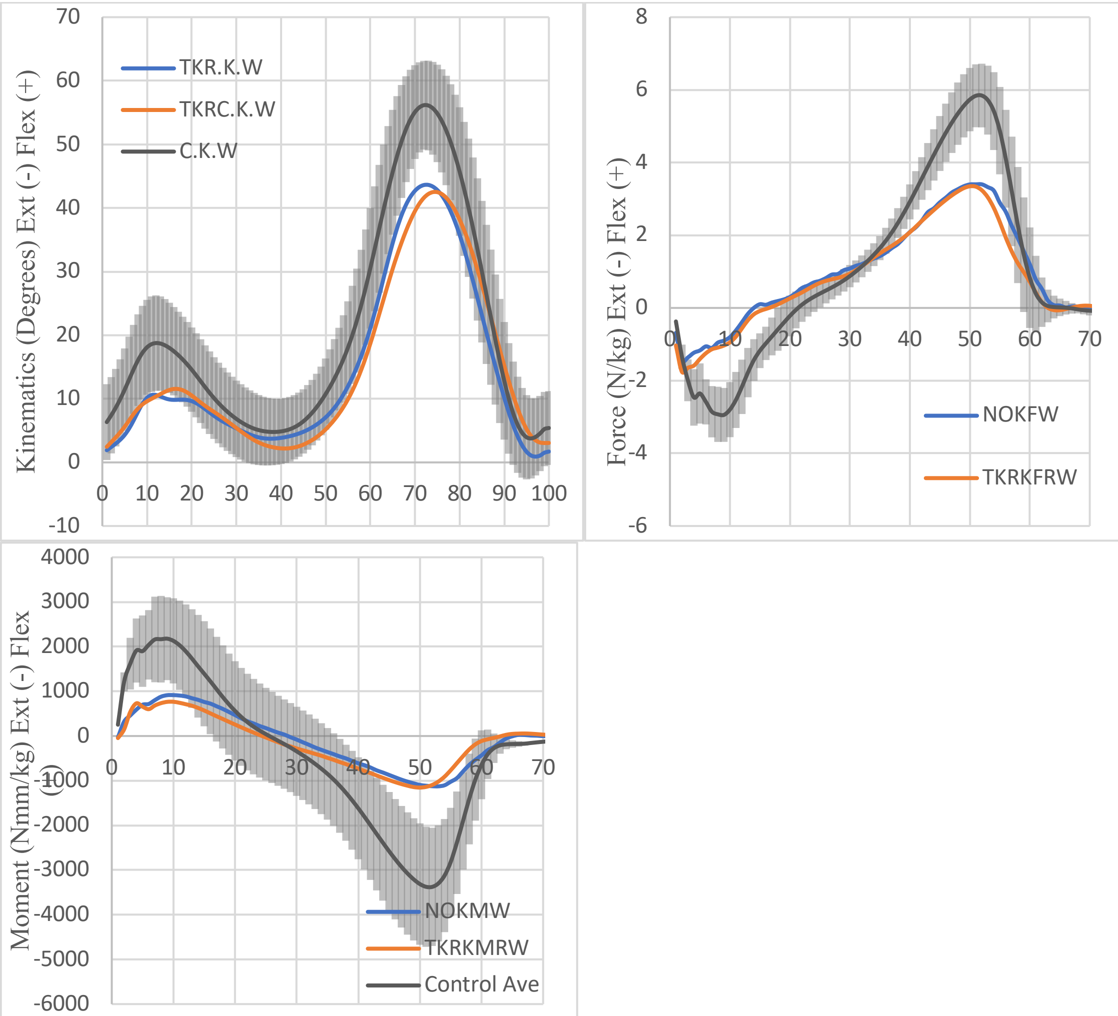

Figure 8: Knee walking: kinematics, force, and moment

The patient averages of the knee profiles show strong correlations, the lowest CF being 0.967, found in the knee moment data where there is no phase of reduced correlation but rather a global trend. The midstance kinematic profile does show a variation in profile with the TKR knee displaying a small plateau rather than a peak.

All three data sets describe a similar profile when comparing both TKR patients' results to the control average, although the magnitude of results is noticeably smaller than the controls. The kinematic, force, and moment results fit into control SD when multiplied by 2, 3, and 2 respectively.

The kinematic results show the control utilizing greater flexion globally, with the greatest variation at midstance and mid-swing peaks. Force data shows reduced extremes at both loading peaks, with the TKR patient results having a steady increase after the initial contact resulting in the first peak being reached earlier in the gait cycle by approximately 7 degrees. The moments generated share a similar profile with peaks being reached at the same point in the cycle.

Knee Running

Due to the poor correlation between the control results, finding the average between left and right results meant a large SD was formed. Having a large SD meant that comparisons between the results were unclear. To simplify the comparison, the left and right control averages were plotted with the relative SD.

1.1.1. Knee

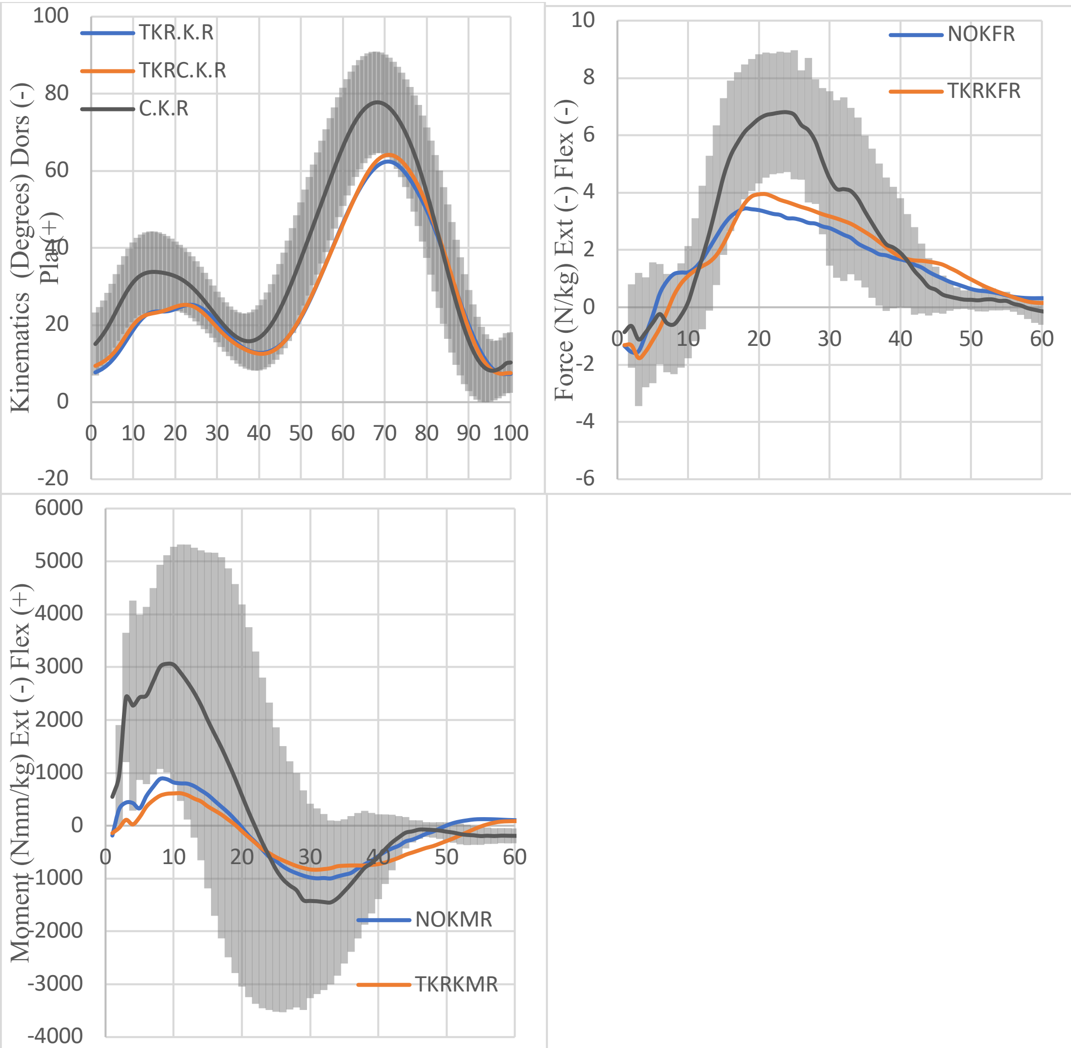

Figure 3: Running knee: kinematics, force, and moment

The correlation of TKR results is very strong in the kinematics results with a CF of 0.999. Both force and moment results display a reduced CF of 0.967 with TKR showing an increased force at the pre-swing phase and the non-operated side showing a greater magnitude of moment throughout.

When comparing TKR to control results, control results display greater magnitudes. All data fit within 2 SD but the results for kinematics and moment are very close to being 1 SD from the control.

The profile of all data shows a high similarity in sharing key events within the gait cycle, except the force pre-terminal stance and pre-swing. The TKR results seem to reach max force sooner and have a more gradual distribution of force towards the end of the stance phase. The kinematic results for control showing a greater flexion angle throughout.

4. Conclusion

This study aimed to highlight key variations between a TKR patient's results to that of the control and to attempt to conclude if the results are similar to that of a healthy individual's gait. The study succeeded in finding and discussing variations in the kinematic, force, and moment results. All TKR results did sit within 3 SDs of controls. However, it is thought that the population size for the control data was too small to draw any solid conclusions.

Throughout the stance phase for walking and running, the gait kinematics of the patient's lower extremities show strong symmetry except for a slight increase in the plantar flexion at the pre-swing for the collateral ankle and hip extension being greater for the operated side. Walking data shows a greater symmetry in the joint forces when compared to running with the running ankles peak value showing the most obvious variation. The force data does show profile differences during the absorption phase while walking and around the peak values while running, which may show load avoidance due to pain or fear.
The moment results show minor variation in the walking results with only a reduced magnitude being highlighted when compared to the control. When running it appears the collateral side moments may overcompensate through the first half of the stance phase with the operated side showing greater values later in the stance phase. The force and moment results show reduced magnitudes, but this is thought to be from habitual behavior of reducing the loads going through the lower extremities.

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