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A computer assessment of the effect of hindfoot alignment on mechanical axis deviation

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ABSTRACT

Lower limb malalignment is a common cause of disability that increases risk of osteoarthritis (OA). Treatment of OA may require an osteotomy or arthroplasty, which mandate accurate evaluation of mechanical loading on the limbs to achieve optimal alignment and minimal implant wear. Surgical planning uses a conventional method of mechanical axis deviation (MADC) measured from the center of the femoral head to the center of the ankle. This method fails to account for hindfoot deformity distal to the ankle. We used a computer model to compare MADC with the ground mechanical axis deviation (MADG), drawn from the center of the hip to the ground reaction point. Average anatomic measurements were analyzed with a range of knee and hindfoot angle variation in single leg stance, double leg stance, toe off and heel strike. MADG was consistently higher than MADC, suggesting a more complete estimate of weight-bearing axis that considers hindfoot deformity.

Introduction

Osteoarthritis (OA) is the most common form of joint disease and often leads to slowly progressive disability in the elderly. [1]. Approximately 27 million people in the United States are currently affected by OA. Moreover, Americans have a 46% lifetime risk of developing OA of the knee [2]. Numerous biomechanical factors, including malalignment of the lower limbs, are associated with increased force across the joints leading to higher incidence and progression of OA of the knee and the ankle [3]. This malalignment can take the form of varus angulation of the distal segment toward the midline or valgus angulation of the distal segment away from the midline. At the knee, varus malalignment has been shown to initiate OA, while both varus and valgus malaligments are associated with increased progression of already existent medial and lateral joint disease respectively. This is thought to be due to shifts in the weight-bearing or mechanical axis of the lower extremity from the anatomic axis [4]. Initial treatment for knee OA may include non-operative measures such as physical therapy, weight loss, and orthotics. Symptomatic degeneration that is refractory to non-operative measures is commonly treated surgically with total knee arthroplasty (TKA).

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TKA is performed based on calculated radiographic mechanical axis deviation with the goal of restoring appropriate alignment [5–8]. Implant longevity has been associated with correct postoperative alignment of the implant. Traditionally, mechanical axis deviation has been measured from the center of the femoral head to the center of the ankle and is called the conventional mechanical axis deviation (MADC). However, numerous studies have indicated that a more accurate measurement of the actual weight-bearing axis would also account for hindfoot malalignment distal to the ankle, including the subtalar joint [7,9–12]. This axis is measured from the center of the femoral head to the ground reaction point and is called the ground mechanical axis deviation (MADG).

The importance of precise alignment for knee implant success cannot be underestimated, as even a minor deviation can lead to increased edge loading, polyethylene implant wear and possible early failure [13]. As such, a more accurate measurement for operative planning that accounts for alignment distal to the ankle, such as MADG, is desirable. To that end, we designed a dynamic computer model to compare measures of malalignment using MADC and MADG. We hypothesize that there is a difference between estimates using these measurement techniques, suggesting that MADG, which accounts for the hindfoot's contribution to alignment, is a more prudent measure of overall weight-bearing axis deviation.

Background

Though no predictable relationship between knee and hindfoot malalignment has been found, it is known that a significant number of patients with knee malalignment will also have some degree of hindfoot deformity [12]. The effect of hindfoot alignment on weight-bearing axis of the lower extremity has been suggested in the literature. Mullaji et al. found that MADG was significantly more deviated from the center of the knee when compared to MADC postoperatively following 169 TKAs. In their study comparing preoperative and postoperative hindfoot alignment in 100 TKA patients, Chandler and Moskal found that TKA performed based on MADC corrected for 50 percent of associated hindfoot malalignment. This finding suggests that the remaining hindfoot malalignment, which contributes to overall lower extremity malalignment, is not accounted for, nor corrected for, using MADC in surgical planning of TKA. In Guichet et al.'s study measuring MADC and MADG on the radiographs of 60 limbs, MADC consistently underestimated MADG for a given subject, concluding that hindfoot alignment has a substantial effect on mechanical axis deviation of the lower extremity.

To our knowledge, this is the first study in the literature that utilizes a computer model of Guichet's equations to compare measurements of MADC and MADG. Use of a computer model allowed the authors to compare these measures over a range of knee and hindfoot angles, providing information on comparisons at both normal alignment angles and the extremes of malalignment. Our results can be compared with the clinical studies cited, where findings suggested that MADG may serve as a more complete measure for evaluating overall lower extremity alignment.

Design considerations

Free-body diagrams of single leg stance, double leg stance, toe off and heel strike were generated and geometrically compared. Tibial length (286.5 mm), femoral length (353.5 mm) and foot height (70.6 mm) were derived from anthropological data of an average adult male in United States [14]. MADC was defined as a line joining the center of the femoral head and the center of the ankle. MADG was drawn from the center of the femoral head to the ground reaction point. This is illustrated in Fig. 1, which shows a free body diagram of a single leg stance. Computer analysis demonstrative of typical clinical scenarios was performed using combinations of knee and hindfoot angles ranging from -10° to 10°.

Description of method/system

Guichet et al.'s predicted trigonometry equations were used to derive MADC and MADG for single leg stance, double leg stance, toe off and heel strike:

$$\mathrm{MADC} = \frac{tf\sin(\gamma)}{\sqrt{t^2+f^2+2tf\cos(\gamma)}} \tag{1}$$

$$\mathrm{MADG} = \frac{\sqrt{t^2+h^2+2nd\cos(\alpha)f\sin(\theta)}}{\sqrt{t^2+h^2+2nd\cos(\alpha)+f^2+2\sqrt{t^2+h^2+2nd\cos(\alpha)f\cos(\theta)}}} \tag{2}$$

where: t = tibial length, f = femoral length, γ = genu-valgum angle, α = hindfoot valgus angle, h = foot height.

$$\theta = \gamma + \sin^{-1}\left[\frac{th\sin(\alpha)}{t^2+h^2+2nd\cos(\alpha)}\right]$$

These equations were programmed in MATLAB (MathWorks, Inc., Natick, MA) and were used to compute the values of MADG and MADC over a range of knee and hindfoot angles. By convention, valgus deviations were considered positive and varus deviations were considered negative. A 3-dimensional graph was plotted to illustrate the differences between MADC and MADG using the same values of knee angle and hindfoot angle in single leg stance, double leg stance, toe off and heel strike.

Status report

Our study used a computer model to analyze mechanical axis deviation by comparing MADC and MADG over a range of knee and hindfoot angles in single leg stance (Fig. 2), double leg stance (Fig. 3), toe off (Fig. 4) and heel strike (Fig. 5) to determine whether hindfoot deformity contributes to overall lower extremity malalignment. MADC and MADG were found to produce different estimates of malalignment at the full range of malalignment angles for all stances. Results of computer analysis are presented in Table 1. On average, MADG was found to exceed MADC from 39 to 53 degrees.

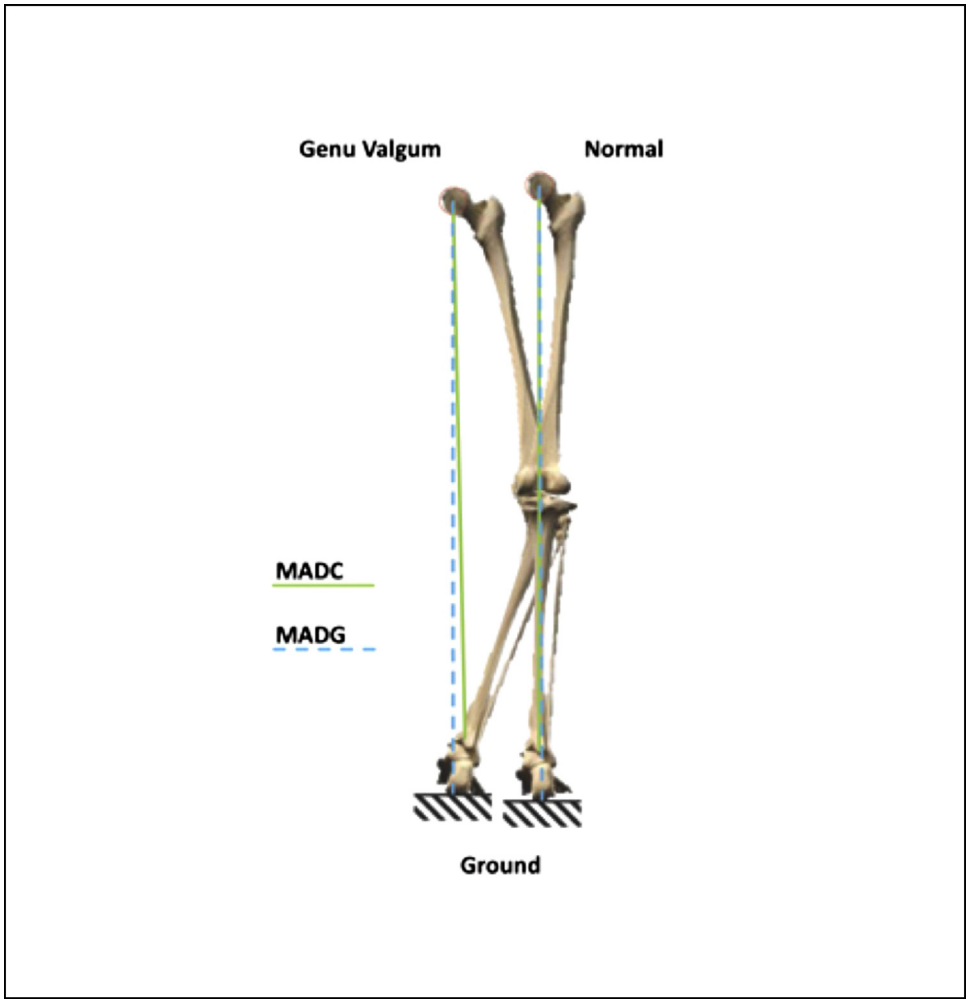

Fig. 1 – Free body diagram of a single leg stance where MADC line represents the measurements taken from center of the hip to ankle and MADG represents the measurements taken from center of the hip to the foot.

Table 1 – Minimum and maximum values of MADC and MADG values for single leg stance, double leg stance, toe off, heel strike with constant values of femur length, tibia length, foot height and varying knee angle and hindfoot angle.

Stance	Hindfoot angle (degrees)	Knee angle (degrees)	MADC (degrees)	MADG (degrees)	MADG-MADC [degrees (%)]
Single leg stance range	−20	−25	−68.48	−116.4	47.92 (70.0)
	30	25	68.48	121.71	53.23 (76.3)
Double leg stance range	−18	−23	−63.08	−107.63	44.55 (70.6)
	28	23	63.08	113.14	50.06 (79.4)
Toe off range	−15	−20	−54.95	−94.06	39.11 (71.2)
	25	20	54.95	99.89	44.94 (81.8)
Heel strike range	−16	−21	−57.67	−98.62	40.95 (71.0)
	26	21	57.67	104.35	46.68 (80.9)

Computer analysis of single legged stance with knee and hindfoot angles of −10° to 10° and 0° respectively, resulted in MADC and MADG values ranging from −27.58 to 27.58 and −42.99 to 42.99 mm respectively. Analysis of single legged stance with knee and hindfoot angles of 0° and −10° to 10° respectively, gave MADC and MADG values ranging from 0 and −6.84 to 6.84 mm respectively. Finally, in the case of single legged stance with both knee and hindfoot angles of −10° to 10°, the MADC and MADG values ranged from −27.58 to 27.58 and −49.67 to 49.67 mm respectively. The range of MADG values for a given stance was found to be greater than that of MADC in all stances. This may be due to the fact that MADC uses a more limited set of parameters (femoral length, tibial length and knee angle) compared to MADG, which considers

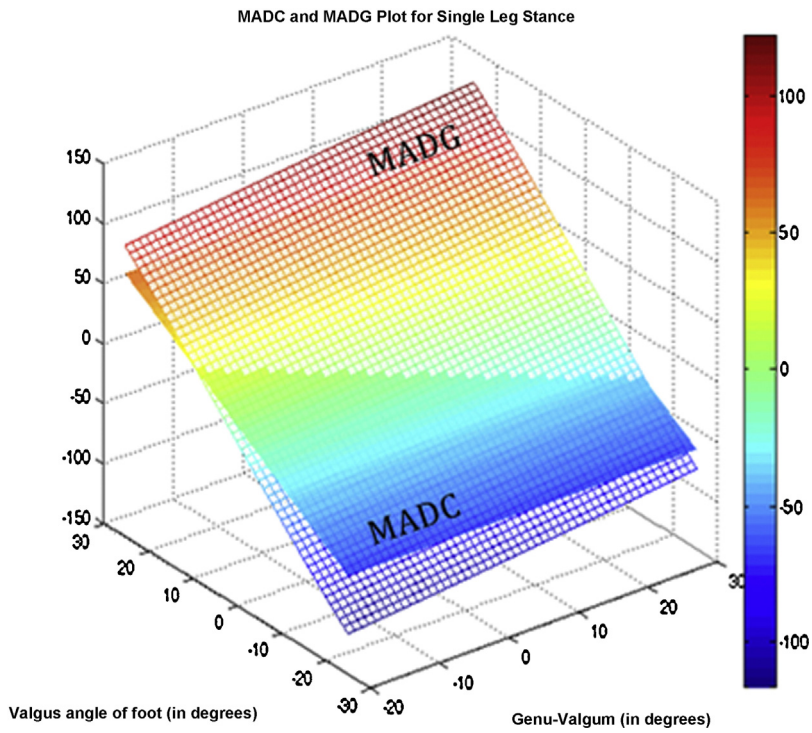

Fig. 2 – MADC and MADG plot for single leg stance where the maximum difference between the two plots is 53.23 mm and the minimum difference is 47.92 mm as knee angle goes from −25° to 25° and hindfoot angle ranges from −20° to 30°.

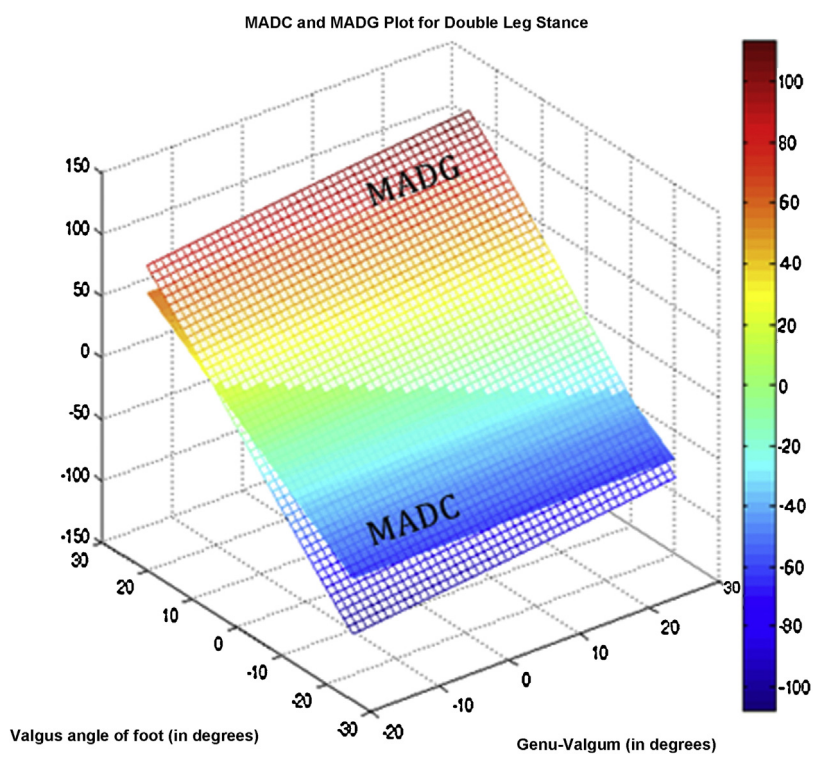

Fig. 3 – MADC and MADG plot for double leg stance where the maximum difference between the two plots is 50.06 mm and the minimum difference is 44.55 mm as knee angle goes from −23° to 23° and hindfoot angle ranges from −18° to 28°.

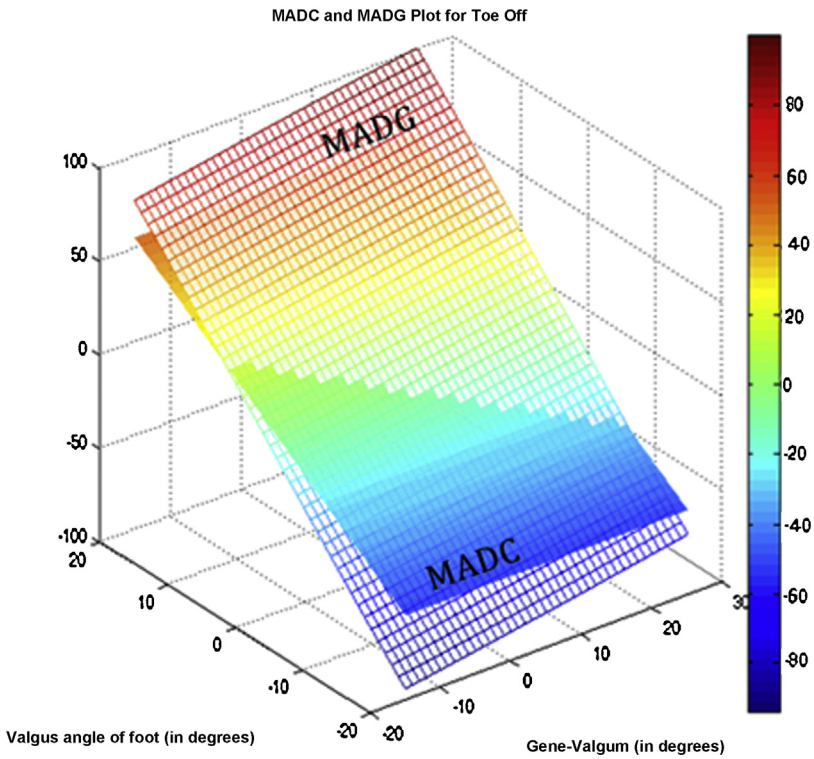

Fig. 4 – MADC and MADG plot for toe off where the maximum difference between the two plots is 44.94 mm and the minimum difference is 39.11 mm as knee angle goes from −20° to 20° and hindfoot angle ranges from −15° to 25°.

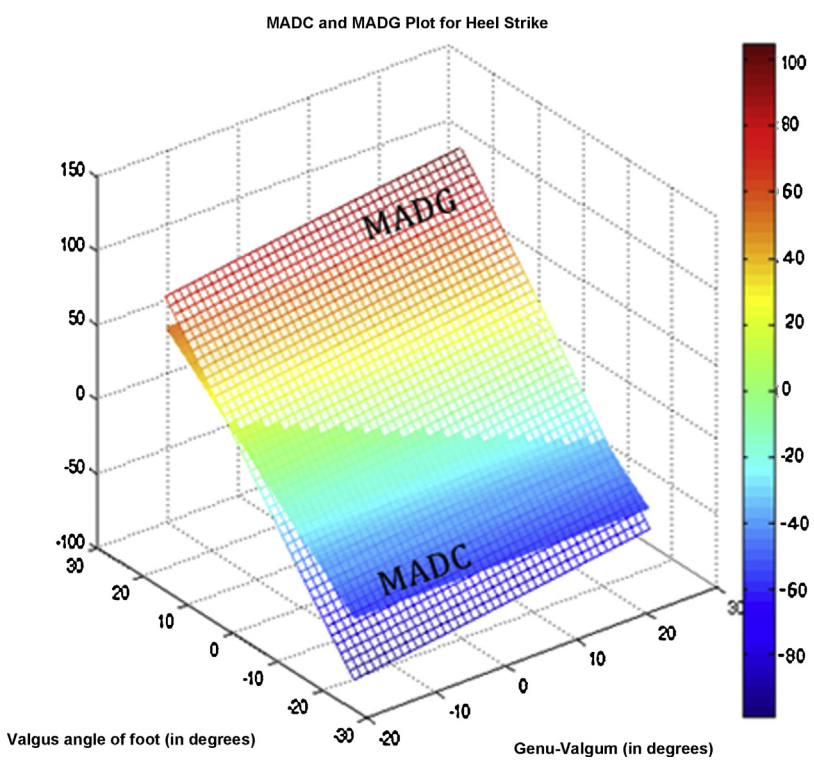

Fig. 5 – MADC and MADG plot for heel strike where the maximum difference between the two plots is 46.68 mm and the minimum difference is 40.95 mm as knee angle goes from −21° to 21° and hindfoot angle ranges from −16° to 26°.

additional factors such as foot height, hindfoot angle, and the angle between the line joining the sole of the foot to the knee and the femur (θ).

Extramedullary and intramedullary cutting guides are currently used to facilitate the tibial bone resection in total knee arthroplasty. Intramedullary guides may be less accurate in those patients with prior deformity of the tibia. Both systems are aligned when proximally, the guide is parallel to the anatomic axis of the tibia and is parallel to the anterior tibial crest. Distally, the surgeon is able to adjust the position of the guide appropriately to ensure appropriate posterior slope resection and minimize varus. The center of the ankle is the landmark for positioning distally, a position that is slight medial to the intermalleolar axis. This current method for distal positioning however will not accurately account for hindfoot deformity since this deformity occurs through the subtalar and midfoot joints.

The MADG technique has limitations demonstrated by gait biomechanics. During gait, the center of the ground reaction point moves with the foot in the sagittal and coronal planes. In ambulation, the subtalar joint ranges approximately six degrees in the coronal plane, while in the stance phase the hindfoot is naturally maintained in valgus angulation [15]. Loading begins at the heel and progresses toward the second metatarsal bone, followed by the first metatarsal head and the great toe. As such, the foot progresses through an externally rotated toe off stance during ground reaction, decreasing the adduction peak moment acting on the knee, which could laterally shift the mechanical axis of the limb [16]. Therefore, evaluating the heel center may not be the optimal estimate of ground reaction point in dynamic loading. In the future, it may be useful to consider the sagittal plane in addition to the coronal plane. Future studies should use actual limb dimensions, angles of deformity and forces to compare MADC with MADG.

Another potential drawback to using MADG in surgical planning for TKA is that it provides information that may lead to a significant increase in deformity correction surgery for the hindfoot. In cases where hindfoot deformity is determined to be contributing significantly to overall lower limb malalignment, hindfoot fusion may be deemed necessary either before or following TKA. The ideal timing of such intervention in relation to TKA remains unclear at this time.

Lessons learned

During single leg stance, toe off and heel strike, loading is likely to create a varus or valgus deformity effect at the knee, because the static symmetry seen in bilateral lower extremity loading is not present. This knee deformity is highest at the extremes of both knee and hindfoot angles, suggesting that hindfoot deformity contributes significantly to actual weight-bearing axis and, thereby, the overall lower extremity alignment. By accounting for the impact of hindfoot deformity, MADG provides an estimate of weight-bearing axis based on a more dynamic model of foot-ankle loading.

The positioning of the hindfoot in context of the mechanical axis is crucial in procedures that address deformity correction of the lower extremity. In the young, active patient with minimal arthritic changes, a proximal tibial osteotomy is performed to correct alignment and minimize progressive changes in the knee joint.

In conclusion, it is essential to accurately evaluate lower limb alignment in surgical planning for TKA. Mechanical axis deviation plays an important role in understanding asymmetrical loading about the knee, which can lead to implant wear [17]. As opposed to the conventional method, a more dynamic model and prudent measure of weight-bearing axis used to calculate mechanical axis deviation for surgical planning would consider the loading of the limb from hip to ground reaction point, described here as MADG.

Future plans

Our results are in agreement with the literature to date, suggesting that MADG may be a more complete estimate of weight-bearing axis. Further evidence for the role of hindfoot correction in achieving lower extremity alignment in TKA patients is warranted. Our model uses only hypothetical values of knee and hindfoot angles to compare MADC and MADG in the current study. Future applications should include use of actual patient data to assess clinical utility.

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