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The Scandinavian Total Ankle Replacement and the ideal biomechanical requirements of ankle replacements

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ARTICLE INFO

Article history:

Received 24 June 2015

Accepted 6 September 2015

Available online 31 October 2015

Keywords:

Arthroplasty

Ankle

Total ankle replacement

Biomechanics

ABSTRACT

The complex anatomy of the articular bone surfaces, ligaments, tendon attachments and muscles makes the ankle joint difficult to replicate in prosthetic replacements. Ever since the early 1970s, which saw the dawn of the first total ankle replacements, there have been numerous other attempts at replicating the joint, often with poor clinical outcomes. The anatomy of the ankle is discussed, followed by evidence of the normal ankle biomechanics and the ideal requirements of an ankle replacement. We focus on the Scandinavian Total Ankle Replacement and evaluate whether these requirements have been met.

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1. Background

The ankle is a complicated joint and understanding the biomechanics, joint compressive forces, stresses as well as the anatomy is key to understanding the ideal requirements in the design of a suitable total ankle replacement (TAR). Nonetheless, there remains limited biomechanical evidence of the possible problems associated with the transverse forces and shank torsional moments involved in TARs.¹ The use of TARs has remained controversial due to the initial poor performance of the earlier models and the preference for arthrodesis, however, medium- to long-term studies of existing prostheses are only now coming to light in the literature with some encouraging results.^{2,3} One such model, the Scandinavian Total Ankle Replacement (STAR) will be

looked into further as to whether it meets the ideal biomechanical requirements of a TAR.

1.1. Anatomy

The tibia, fibula, talus and calcaneus make up the main bones of the ankle, articulating with nearby bones via the talocrural, subtalar and midtarsal joints. It is surrounded by an array of muscles, tendons and ligaments (lateral and medial collaterals), which are crucial factors in joint stability. The lateral collateral ligaments are comprised of the anterior talofibular, the calcaneofibular and the posterior talofibular ligaments. The medial collateral ligament (or deltoid ligament) is thicker and stronger than those of the lateral collaterals. Important tendons include the achilles (dorsiflexion) as well as anterior and posterior tibial tendons (inversions and eversion respectively).

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Abbreviations: TAR, total ankle replacement; STAR, Scandinavian Total Ankle Replacement.

<http://dx.doi.org/10.1016/j.jor.2015.09.002>

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The principal muscles effecting movement are the calf muscles (gastrocnemius and soleus), peroneals (peroneous longus and brevis) and tibial muscles (anterior and posterior tibialis). The ankle is further surrounded by the joint capsule.⁴

1.2. Biomechanics of the normal ankle joint

An understanding of the biomechanics around a normal ankle is essential for them to be reproduced in the design of prostheses. A variety of methods have been used to investigate the ankle joint, including computer models, Roentgen stereophotogrammetry (the use of X-rays to assess three-dimensional micromotion of a prosthesis) and fluoroscopy, utilising both in vitro and in vivo methods.⁵

A number of disparate models have been proposed, from a simplified hinge joint to a ball and socket joint. This oversimplification is arguably the cause of the first generation TARs' poor results. The ankle is now regarded as a multi-axial joint, with rolling and sliding movements.⁶ Dettwyler et al.¹ confirmed the results from previous studies that the amount of vertical rotation between the talus and the tibia in the vertical plane upon walking is around 5–6°. The collateral ligaments and distal tibiofibular ligaments were shown to be important in preventing the rotation of the talus upon the tibia whilst internally or externally rotated.^{7,8} The surface area of the ankle, hip and knee joints are comparable, yet the ankle contact area during loading is only one third of that experienced in either of the hip or knee at 11–13 cm²,⁸ hence, greater stresses are transmitted through the joint, 64% more than in the knee and 45% more than in the hip.

The centre of contact within the ankle joint moves anteriorly upon dorsiflexion and laterally upon eversion with the greatest degree of contact with the talus at dorsiflexion. Load distribution through the talus is determined principally by the position of the ankle as well as the surrounding ligaments, with the majority being transferred through the dome. The medial and lateral talar facets have greater loads during inversion and eversion, respectively.⁶

The fibula, interosseous membrane and subtalar complex absorb energy around the ankle, reducing the amount of force through the joint.⁶ Cheung et al.⁹ used a 3D computer model to show the maximum von Mises stresses to be through the talus and calcaneus upon standing. Renstrom et al.¹⁰ showed that two ligaments, the anterior talofibular and the calcaneofibular ligaments behave synergistically with each other, highlighting the importance of strain in the stability of the joint. Tochigi et al.¹¹ used a geometrical model to explicate the different stress changes in the articulating surface between the tibia and talus, quantifying its contribution towards joint stability, namely that it provides 70% of anterior/posterior stability, 50% of inversion/eversion stability and 30% of internal/external rotation stability.

Different values exist for the amount of ankle coupling, and there is a relationship between the amount of tibial rotation and the degree of inversion/eversion of the ankle. Torque around the long axis of the foot depends on vertical loading, foot position, ligaments, muscles and individual variances.¹ During the different phases of gait, computer models have been able to demonstrate the various ankle joint forces experienced. Patil et al.¹² showed that the ankle joint exerts

resultant forces of around two times an individual's body weight during all phases of the gait cycle. The highest main stresses in tension and compression were experienced during push-off. Forces between 5 and 7 times an individual's body weight are experienced through the ankle during the stance phase and around 9–13 times during the same phase whilst running, which are greater than those exerted in the hip and knee. Heel-to-toe running at 4.5 m s⁻¹ generates a force of nearly three times the body weight.¹³ Contraction of the calf muscles (gastrocnemius and soleus muscles) during the late stance phase is responsible for the majority of the compressive forces experienced in the ankle. Here the ankle is plantarflexed, and the anterior tibial compartment helps it to dorsiflex.

1.3. Ideal requirements of a TAR

The ideal requirements of a TAR must be able to replicate the biomechanics of a normal ankle joint as much as possible, not just as a simple hinge joint, but as a multi-axial joint with a combination of rolling and sliding movements. The range of motion of a normal ankle joint in order to partake in everyday activities should be taken into consideration, noting that middle-aged and elderly individuals for whom a TAR would be appropriate may not be as active as young individuals, hence may not require as large a range of movement. Relief of pain and the restoration of functional movement to the patient's pre-morbid condition are the main clinical priorities.⁶

The TAR should either exactly replicate the original anatomical geometry of both articular surfaces and ligamentous structures or should aim to restore compatible function of them both, albeit with slightly non-anatomical articular surfaces.⁶ It became readily apparent in earlier designs that too much emphasis was made on ensuring anatomical congruency. These constrained or semi-constrained devices meant that higher stresses would be experienced over the fixation, compared with the more recent unconstrained prostheses, which granted more polyaxial movement and a more even distribution of forces. Synergy between contact surfaces and ligaments is vital to the design of an ideal TAR.¹

Procter et al.¹⁴ mentioned that in order to prevent prosthetic loosening, shear forces should be transferred to an antero-posterior axis and the moments should centre around a vertical axis. The prosthetic articular surface must be compatible with the geometry of the ligamentous structures.⁶ The correct alignment of the hind foot prevents abnormal stresses and eccentric polyethylene wear. A cadaveric study showed that large forces are transmitted around the long axes of cemented ankle prosthesis, hence uncemented prostheses are now preferable.¹⁵

It is important to note that these ideal requirements must be compared with that of fusion surgery, which has long been considered the 'gold standard'. Important determinant factors include patients who are middle-aged or elderly, anatomically alignment of the ankle and heel, well preserved range of motion and adequate bony support.

1.4. The STAR

The STAR was first implanted as a cemented prosthesis in 1981. However, since 1989 the STAR has been a congruent

cylindrical three-part prosthesis coated with hydroxyapatite. This coating allows for stronger bone next to the prosthetic parts as well as providing for better gait motion. It is comprised of a two-fin tibial component and single-fin talar component. The talar component precisely matches the anatomical shape of the talar dome with wings on either side to articulate with the tibia and fibula (allowing for greater fixation) and a crest on the superior aspect.³

The prosthesis allows up to 10° of dorsiflexion and 35° of plantarflexion,¹⁶ though it does not permit pronation/supination at the planar floating bearing-tibial interface, which may be related to the poor transverse plane stability of the planar-to-planar interface between two of the components.¹

The shear forces have been designed to be kept low by ensuring minimal constraint, and the amount of polyethylene wear has also been lessened by establishing maximal congruency between articular surfaces. Ribs and grooves provide a sharp limiting interface to entrap the meniscal bearing, which limits the floating of the bearing core and is designed to reduce dislocation and separation, however this does have the adverse effect of increased polyethylene wear.¹⁷

Giannini et al.¹⁸ showed that as the STAR featured curved and planar interfaces for the meniscal bearing to allow for internal/external rotation, rotation is achieved from the tibial meniscal interface. This meniscal bearing was designed to reduce the stress on the ankle by allowing side-to-side movements as well, but this is unlikely to occur due to the high level of medio-lateral entrapment of the talus within the tibial mortise. The reduction in friction between the articulating components means that much of the ankle stability and joint mobility is left to the provision of the surrounding muscles and ligaments. To date there have been no studies looking into their role in doing so.

When the geometry of two isometric ligaments and the shape of one articular surface are known, the shape of the complementary surface of the other bone compatible with ligament isometry can be deduced. The prosthetic talar surface has been shown to have a larger curved radius than the natural talus in some recent designs (including the STAR), rendering them incompatible with physiological ligament function,⁷ and therefore, it does not restore the physiological pattern of ligament tensioning.⁶

Cadaveric studies have compared normal ankle biomechanics with those with STAR ankles. They have shown there to be no significant changes during inversion/eversion, significant reduction in dorsiflexion/plantarflexion, significant increase in internal rotation and significant reduction in external rotation.¹³

There is great importance in the positioning and sizing of the ultra-high molecular weight polyethylene bearing surface. Tochigi et al.¹¹ in a cadaveric study showed there to be anterior lift-off of the bearing surface when the talar component is positioned anteriorly and increased loads, i.e. edge loading on the posterior side of the bearing surface, if the bearing surface was undersized. Subfibular impingement may arise if the bearing surface is undersized, reducing contact pressure on its anterior aspect. Edge loading increases wear of the bearing surface and the risk of failure.

Wood et al.¹⁷ looked at 200 STAR ankle replacements and found 9 of them to have experienced edge loading of the

bearing surface. A separate case report mentioned a patient, who underwent revision surgery on their STAR replacement for a fractured fibula having developed a cyst following edge loading of the bearing device due to a varus talar tilt.¹⁹ Other studies have also reported failures of the device due to the bearing surface, but have not given biomechanical rationale for the cause of the failure, although combinations of varus/valgus deformities and ligamentous instability make for convincing rationale.²⁰

Despite claiming to 'simulate the original articulating surfaces of the ankle joint to enable proper movement of the parts', this is only true for the talar component, whereas a major change on the tibial component has recently been introduced to resolve this. Recent clinical results are promising, with 95% survivorship after 6 years, however, there is very little literature providing evidence of how the new tibial components seem to more closely simulate the mechanics of a native ankle joint.

2. Conclusion

Despite the advances and revisions in the STAR prostheses, research still needs to take place to critique and improve on existing designs so as to improve on the ideal requirements for replacing the ankle. The main cause of failure appears to be component loosening, either through excessive wear or improper positioning during surgery. Although clinical outcomes have been reported quite extensively, the reasons as to why they have failed have not been found, and this is essential in order to produce a more ideal TAR. Modelling and experimental evidence support careful restoration of the compatibility between the combination of prosthetic surface designs and the positions of ligaments, which has all too often been neglected. Huge advances have been made in its development, but there is still much scope for improvement in order to bring the results of TARs and the STAR in line with results from those seen in hip and knee replacements.

Conflicts of interest

The authors have none to declare.

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