RESEARCH ARTICLE

Alteration of Lower Limb Kinematics and Kinetics due to Bilateral Triple Arthrodesis

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Abstract

Objectives: The study aimed at discovering the existing differences in lower limb joints' kinematics, and EMG signals of 4 particular muscles of the ankle joint during gait, between normal subjects and patients with bilateral triple arthrodesis.

Methods: In this research, a 3D motion analysis system was used and joints' angles were calculated using a MATLAB code, and based on the data collected from markers movements, for patients with bilateral triple arthrodesis and normal subjects. Moreover, the EMG signals of ankle muscles in each subject, and the graphs of mean plus and minus standard deviation of lower limb joint angles and muscles' EMG were calculated by MATLAB.

Results: In all patients, an initial ankle eversion and valgus deformity were observed in their knee joints. In addition, for all patients, the maximum knee extension was less than that of the average value of the normal subjects. Furthermore, the results of the electromyography showed that, in all patients, delay occurred in gastrocnemius and soleus muscles in maximum contraction in their EMG signals. Besides, during the early stance phase of gait cycles, the mean value of EMG of peroneus brevis muscle for patients was more than that of normal subjects.

Conclusion: Atrophy of four ankle muscles including (soleus, lateral gastrocnemius, tibialis anterior and peroneus brevis), also limitation of joints movement were observed in patients, compared to normal subjects. Based on the results of this work, in order to reduce further musculoskeletal disorders in patients who underwent bilateral triple arthrodesis surgery, there is a serious need to use physiotherapy after the surgery.

Level of evidence: IV

Keywords: Ankle joint kinematics, Bilateral triple arthrodesis, Electromyography, Gait cycle, Muscle atrophy

Introduction

Arthrodesis is a surgical procedure in which two or more bones of a joint are fused together. Arthrodesis is typically performed to correct joint or bone deformities caused by fractures, arthritis, or developmental defects. A frequently used arthrodesis procedure is the bilateral triple arthrodesis (BTA, two side arthrodesis) fusion of the ankle, which limits talonavicular, calcaneocuboid, and talocalcaneal joints motions. Not only does BTA limit the motion of the fused joints, but it also constrains the motions of neighboring joints. For example, following BTA, ankle dorsiflexion and plantar flexion are reduced, and ankle internal-external rotation and inversion-eversion are essentially lost.[1] Reduction in joint range of motion also affects muscles, causing chronic atrophy and weakening.[2] BTA, due to its destructive effect on muscle weakness and limitation in joints movement, can likely cause arthritis in the affected joints after a while.[3]

High-speed, 3-dimensional kinematic analyses have been used, by numerous researchers to date, to study joint function following surgical interventions and repairs. For example, Stevens *et al*. showed that arthrodesis of the first metatarsophalangeal (MTP) joint was associated with

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compensatory motions at the ankle and the forefoot because it was associated with a reduced eversion and an increased internal rotation of the hind-foot, and an increased supination of the forefoot.[4] Joveniaux *et al*. showed that subtalar arthrodesis is associated with an increase of the onset and rate of progression of osteoarthritis in neighboring joints.[3] Ota *et al*. suggested that, based on a theoretical modeling approach, ankle arthrodesis patients have a reduced sagittal and coronal plane motion of the hind foot during gait, compared to non-operated controls.[5] On the other hand, Singer *et al*. reported that total ankle arthroplasty, but not ankle arthrodesis, allowed for virtually normal gait following surgical intervention.[6]

The long-term effects of ankle arthrodesis have also been studied by some researchers to date. Trouilier *et al*. observed that patients with ankle arthrodesis have a reduction of movement in the hindfoot in the sagittal plane.[7] Zhang *et al*. performed hind foot arthrodesis in cadavers and showed that there is a reduced foot range of motion in all directions, with severe limitations in internal or external rotation and inversion or eversion.[1] Ogrodzka *et al*. employed gait analysis in patients with ankle arthrodesis, and showed that there is significant knee valgus deformity, and reduction in sagittal plane hip motion, compared to a non-operated control group.[8] Similarly, Weiss and co-workers showed that patients with ankle arthritis experience considerable changes in knee flexion and hip extension, following ankle arthrodesis.[9] The long-term effects of ankle arthrodesis have also been investigated radiographically, and position of fused joints were evaluated on different planes just by using radiographic procedures.[10-12] Segal *et al*. compared patients following ankle arthrodesis and ankle arthroplasty, and found that arthrodesis resulted in a decrease in ankle and hip range of motion for walking, while arthroplasty resulted in an increase in the ankle, and no change in the hip range of motion on the sagittal plane.[13] Muscular activity of lower limb muscles are also affected by ankle arthrodesis.[14,15] Hejazi *et al*. estimated the forces of four lower limb muscles in patients following ankle BTA, and compared the muscles forces to the corresponding EMG activities.[16] They found a good agreement between the required forces and the corresponding EMG activities, and also found that the EMG and force requirements following BTA were different from those of subjects with normal ankle joints.[16]

In spite of the clinically promising results of ankle arthrodesis, there are some disadvantages associated with these procedures. The major disadvantages are muscular atrophy, reduced range of motion at the target joint, and compensatory changes in kinematics and kinetics of joints in the vicinity of the target joint.[2,16] Moreover, reducing joints' range of motion, in the gait cycle is another disadvantage of the arthrodesis. Based on previous studies, it is known that changing the arthrodesised joints' range of motion can affect the neighboring joints, as well as the corresponding muscles' activities.[7,8]

In this study a 3D motion analysis system was used to identify the effect of bilateral triple arthrodesis (patient with triple arthrodesis in their both feet, with similar arthrodesis surgery procedures and no history of diseases) on the kinematic behavior of neighboring joints and ankle muscle power. In this paper using the kinematic data of lower limb joint and EMG of muscles, we investigated the correlation between triple arthrodesis in two sides of feet and limitation in other joints like knee. Moreover, the activity of muscle in the patients and also the effects of peroneus brevis and calf (gastrocnemius and the soleus muscles) weakness on increasing the abnormality of angle in the other joints in patients, were investigated.

Materials and Methods

Ten subjects, five patients with BTA, and five normal subjects, were recruited for this study. The BTA patient group was comprised of two females and three males (mass = 66 ± 10 kg; age = 32 ± 3 years; height = 1.68 ± 0.11 m; and BMI = 23.4 ± 3.8), and the mean follow-up duration after surgery was 2.7 years. The normal subject group was comprised of two females and three males with no ankle abnormality, or musculoskeletal disorder or pain (mass = 64 ± 8 kg; age = 26 ± 2 years; height = 1.73 ± 0.11 m; and BMI = 21.6 ± 2.9). All subjects provided written informed consent and the experimental procedures were approved by the ethics committee.

For gait analysis tests, 15 retro-reflective spherical markers were used, according to the Helen Hayes marker set protocol.[17] The markers were located on the anterior superior iliac spine (ASIS), lateral femoral condyles, heel, malleolus, thigh, shank, fore-foot, and sacrum.[17] Six cameras (Vicon, Motion System, Oxford, UK) were used to collect 3-dimensional gait data at the frequency of 100 Hz. All subjects performed three walking trials,[18] and the gait cycle was defined to start at heel strike of the right foot and ended with the heel strike of the same foot.[19]

Muscle activity was measured using surface EMG on the lateral gastrocnemius, soleus, tibialis anterior, and peroneus brevis [Figure 1]. EMG electrodes were placed along the axis of the muscle fibers by determining the position of the muscle and its origin and insertion of the muscles, according to a guide once the origin and insertion of the target muscles had been identified for surface EMG electrode.[20] In this study, locations of the electrodes for recording surface EMG and origin and insertion and bulk of muscle were chosen according to De Luca .et al. and an surface anatomy expert [20] and EMG signals were recorded at the frequency of 1000 Hz, and were normalized to the maximum voluntary contraction (MVC). MVC test, or maximum voluntary contraction, was performed by each subject, according to anatomical guide for the electromyographer.[21] each subject performed three maximal voluntary contractions (MVC). Subjects were told to build up force to a maximum over a 2-3 s period and then hold the maximum force for another 3s prior to relaxing. A 30 s rest was strictly enforced between three contractions for a given joint position, and a 90 s rest between different joint positions. Subjects could ask for a longer rest period if they felt the need for that.[21] Kinetic and kinematic data were filtered according to previous study.[22-24] Force platform data were sampled at a frequency of 200 Hz, and force data and kinematic data were filtered using a fifth-order Woltring filter, with a cut-off frequency of 10 Hz.[22-24] The raw EMG signals were filtered by BioProc software using Butterworth

filter with cutoff frequency of 10 Hz. to ensure smooth trajectories.[22,25] Joint angles expressed in the three anatomical planes: sagittal, frontal, and coronal. The lower limb segments were considered as seven rigid bodies: two shanks, two feet, two thighs, and the pelvis.[17] Joint angles were measured and defined according to a plug in gait manual.[26] in this research, the hip, knee, and ankle joint angles were obtained, in 3D, by using surface markers. The three-dimensional data of the markers, attached to the body, were obtained by six cameras, and then the angles between two frames were found using the MATLAB code specifically written for this study. Joint angles were expressed in the three anatomical planes, i.e., sagittal, frontal, and coronal planes. The lower limb segments, i.e., two shanks, two feet, two thighs, and the pelvis, were considered as rigid bodies.[17] the lower limb joint angles specify the relative orientation of the distal segments with respect to the proximal reference segment, which can be derived using a rotation. Finally the matrix of the unknown angles, were calculated using commercially available MATLAB software [Figure 1].

Figure 1. Electrode placement of the peroneus berevis, tibialis anterior, lateral gastrocnemius, and soleus from the left to right, respectively

Results

The lower limb gait kinematics for normal subjects and patients are in agreement with previous studies [Figure 2].[17] As can be seen in [Figure. 2], dorsiflexion and plantar flexion [Figure 2a] and inversion and eversion of the ankle [Figure 2b] during the swing phase was reduced in the BTA patients, compared to the control subjects. Ankle inversion at toe-off was increased in BTA patients, compared to controls [Figure 2b]. In all patients, there was an extreme initial eversion of the ankle, compared to that seen in the control subjects [Figure 2b]. The maximum knee extension angle at toe-off and early stance was less in all patients, compared to the mean angle measured in the normal subjects [Figure 2c]. The maximum hip extension angle for BTA patients was smaller than that of the control subjects [Figure 2f]. Hip joint angles in the frontal plane were similar in BTA patients and control subjects, except for the early stance phase, where hip adductions of in BTA patients were less than those of control subjects [Figure 2g]. External and internal hip rotation during stance was also reduced in patients compared to control subjects [Figure 2h].

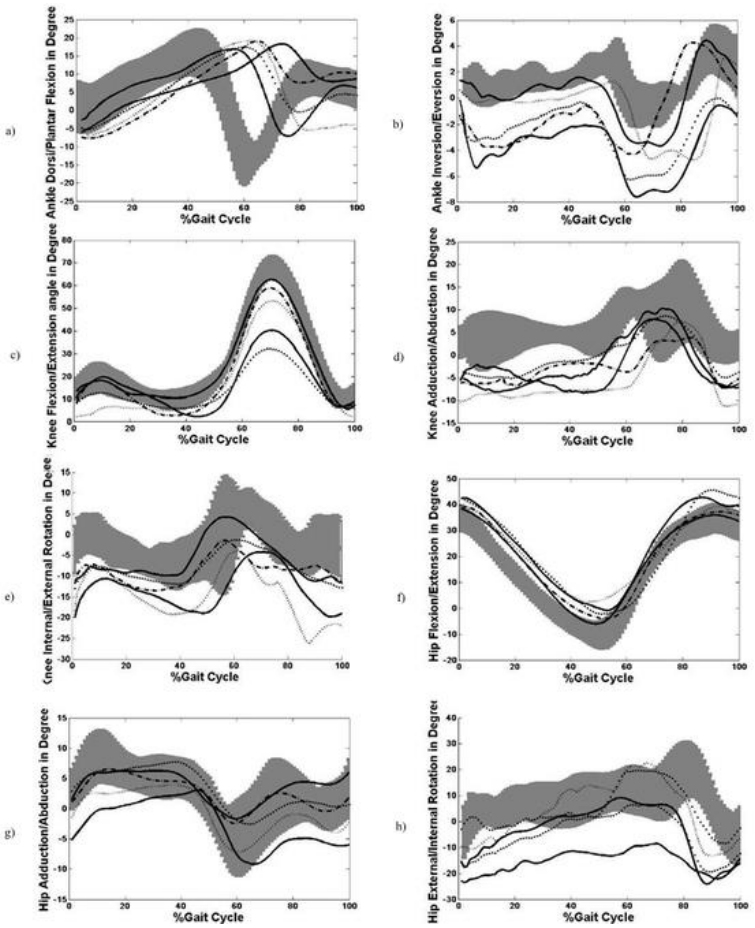

Figure 2. Ankle, hip and knee joints various range of motion during gait (in degree). Gray band means the joints range of motion plus and minus standard deviation for normals, and the lines (including dash and solid lines) are related five patients with triple arthrodesis

The EMG patterns of the four ankle muscles, i.e. soleus, lateral gastrocnemius, tibialis anterior, and peroneus brevis for normal subjects are in agreement with previous studies [Figure 3].[25,27] As can be seen in [Figure. 3], the EMG patterns of muscles were different in patients in comparison of normals. For instance, normalized tibialis anterior's EMG in the early phase of stance was less in patients than controls [Figure 3c]. Also, maximum EMG activity in gastrocnemius and soleus muscles of patients occurred later in the gait cycle than in the control subjects [Figures 3a and 3b]. The calf muscles in the BTA patients were generally not as active as in the controls [Figures 3a-c], but peroneus brevis activity was greater than normal for the BTA patients in the early phase of stance [Figure 3d].

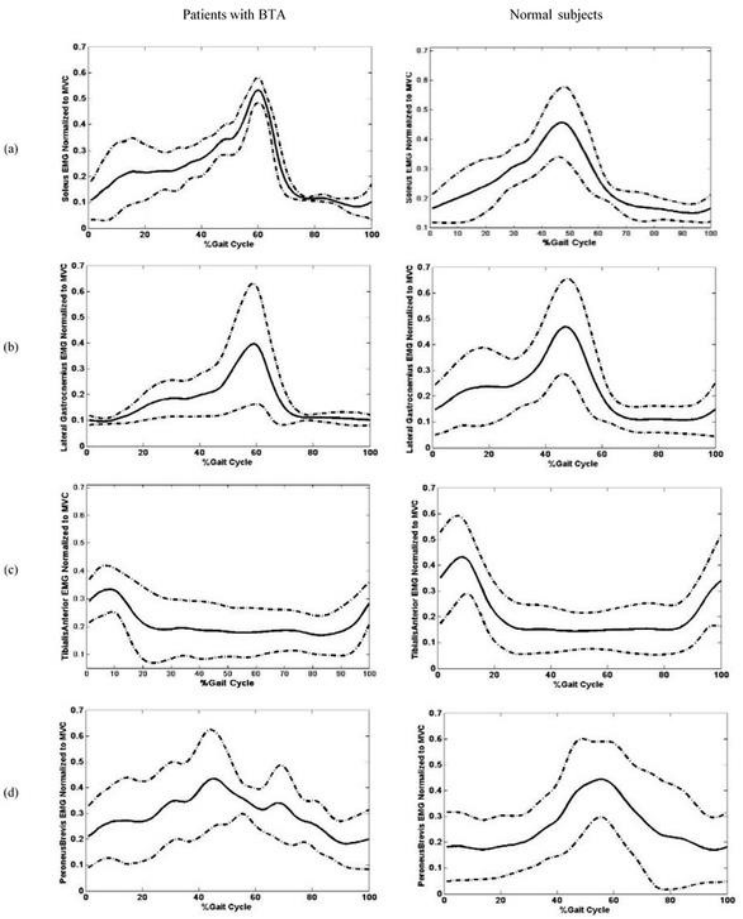

Figure 3. The mean (solid line) and plus and minus (dash lines) of standard deviation of the EMG signal normalized to the maximum voluntary contraction (MVC) - for patients with BTA (left column), and normal subjects (the right column) and "a "graph is for soleus, "b" for lateral gastrocnemius, "c" for tibialis anterior and "d" for peroneus brevis muscle

Discussion/ Conclusion

Although arthrodesis is a generally accepted surgical procedure for the treatment of severe arthritis, trauma and other deformities of bones and joints, but its short- and long-term implications are not fully understood. Some of the negative side-effects of arthrodesis are: reduction in the range of motion of the target joint; reduced muscle activation; muscle atrophy and weakness; and causing abnormal, "compensating" movements in neighboring joints.[2,3] Determining the negative side-effects of arthrodesis can be the first step for improving surgical procedures and adapting rehabilitation regimes for arthrodesis patients. Understanding the long-term effects of bilateral triple arthrodesis can help us find improved method for BTA thereby increasing the likelihood of knee joint osteoarthritis [Figure 2c]. Another side effect of bilateral triple arthrodesis surgery is a weakening of the calf muscle [Figure 3a&3b], thus patients are advised to receive physiotherapy treatment surgery to prevent destructive long-term effects on the musculoskeletal system.

In this study, it was found that maximum knee flexion angle at toe-off in early stance in BTA patients is less than the mean value of the control subjects [Figure 2c]. It was also found that, in agreement with a previous study on patients with knee arthritis,[28] that the BTA patients contacted the ground with a more extended knee than the control subjects [Figure 2c]. In patients with BTA, a decreasing knee range of motion, probably caused by pain, is associated with knee extensor muscle atrophy which is in agreement with this study, which in turn, may increase the risk for knee joint arthritis.[29] Therefore, BTA, although providing relieve for ankle pain and discomfort, may predispose the knee for early onset and an increased rate of osteoarthritis progression [Figure 2c].

It is known that one of the functions of peroneus brevis muscle is the ankle eversion, and it can be seen that in all patients more ankle eversion occurred [Figure 2b], and also more activation in peroneus brevis muscle [Figure 3d]. In patients with BTA, more activation of peroneus brevis muscle, and weakness in calf muscle can cause an increase in their ankle eversion [Figure 2b]. Based on these findings, BTA patients may need to be advised to actively invert the foot to counteract the abnormal eversion. Moreover, since the calf muscles in BTA patients, were found to be weaker than normal subjects [Figure 3a], strengthening of these muscles can be advised as an important aspect of rehabilitation programs. The patterns of lower joints kinematic data and EMG signal of muscles of patients with BTA (two side arthrodesis) may assist future procedures of surgery in patients with bilateral trauma to the ankle.

In this study, each segment was assumed to have rigid body motion, whereas it has been well documented that the foot is clearly not rigid. Also, the number of subjects was small, thus generalization of the results needs to be made with this limitation in mind. One of the novelties of this study was that analyses were made on patients with bilateral BTA, so that gait cycle would not be affected by another healthy leg or ankle or foot (in single arthrodesis), and the long term effect of the surgery could be determined. It is thought that the results of this study enhanced our understanding of the long-term kinematic effects of ankle joint BTA, and it is hoped that this kind of study can help improve surgical approaches and rehabilitation programs. In this study, after calculating the joint angles in patients who underwent bilateral triple arthrodesis surgery, it can be concluded that the range of motion of neighboring joints was altered compared to normal control joints. Thus, bilateral triple arthrodesis surgery has side effects on the neighboring joints and muscles that need to be carefully accounted for by surgeons and patients [Figure 3c&3b]. For instance, we found that triple arthrodesis surgery limits the movement of the knee joint, which may cause knee extensor muscle weakness,

to increase strength in their calf muscles. In summary, surgeons and patients should be aware of the side effects of, bilateral triple arthrodesis surgery, including a reduction in joint excursion and lower limb muscle weakness. Similar to

other studies in this field of research, i.e., orthopaedic biomechanics, this study had limitations. For instance, in calculating joint angles, the possible effects of soft tissues on joint angles were not taken into account. The presence of muscles and other soft tissues affects the angle calculations, and this should be kept in mind when interpreting our results. Another limitation was the small number of subjects, as it was difficult to find patients who were operated by the same surgeon and had the bilateral surgery at the ankle joints as required for this study. Also, we wanted patients of similar age and similar ankle injury, further decreasing the number of potential participants.

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