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ORIGINAL ARTICLE

The impact of proximal fibula resection on foot and ankle biomechanics: A radiological and pedobarographic evaluation

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ABSTRACT

Objectives: This study aims to evaluate whether changes in ankle radiological parameters following fibular head resection due to tumors lead to ankle instability and/or ankle arthritis and to assess the impact of resection on clinical outcomes using pedobarographic analysis and pain and function scales.

Patients and methods: Between January 2005 and January 2023, a total of 30 patients (10 males, 20 females; mean age: 33.9±13.8 years; range, 10 to 67 years) who underwent proximal fibula resection were retrospectively analyzed. We assessed fibular rotation using axial ankle magnetic resonance imaging (MRI), fibular length, talar tilt angle, and talotibial angle changes using X-ray, foot load distribution changes through pedobarographic measurements, and clinical outcomes using the Visual Analog Scale (VAS) and Musculoskeletal Tumor Society (MSTS) scores.

Results: Fibular length and rotation were significantly reduced, while talar tilt and talocrural angle were higher on the operated side. Additionally, load balance and maximum pressure in the second to fifth toes (T2-5 regions) were significantly lower on the operated side. The mean VAS score was 1.5±1.4 and the mean MSTS score was 26.8±2.9. The MSTS scores showed weak negative correlations with differences in fibular length, fibular rotation, talar tilt, and talocrural angle, none of which were statistically significant (r=–0.35, –0.3, –0.1, –0.1, p=0.06, 0.1, 0.62, 0.61). In contrast, the VAS score showed a significant positive correlation with fibular length difference (r=0.45, p=0.01), while correlations with other parameters were not significant. A positive correlation was observed between the percentage of resected fibula and differences in fibular rotation (r=0.67, p<0.001), fibular length (r=0.73, p<0.001), talocrural angle (r=0.49, p=0.003), and talar tilt angle (r=0.66, p<0.001); this correlation was more pronounced in patients with more than 30% resection.

Conclusion: Proximal fibula resection for tumors involving the fibular head leads to significant changes in ankle radiological measurements and load distribution. Despite these changes, clinical outcomes, as reflected by low VAS scores and high MSTS scores, indicate generally favorable patient-reported outcomes.

Keywords: Ankle, foot, pedobarography, proximal fibula resection, proximal fibula tumors.

Benign aggressive and malignant tumors involving the fibular head are rare and accounting for only 2.5% of all primary bone tumors.[1] About a quarter of all primary bone tumors involving the fibula are malignant and about a quarter of all benign and benign aggressive bone tumors of the fibula are giant cell tumors of the bone (GCTB).[2] Benign aggressive and malignant tumors involving the proximal fibula necessitate the surgical resection of the proximal fibula.[2,3]

The extensor digitorum longus originates from the anterior upper third of the fibular body, the lateral part of the tibial condyle, the proximal interosseous membrane, and the intermuscular septum, while the peroneus longus originates from the head and lateral upper two-thirds of the

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fibula, the tibiofibular intermuscular septum, and the lateral tibial condyle.[4,5] During surgery, these muscles are removed from their origin, which can result in negligible differences in foot biomechanics and gait imbalance. These disparities can be attributed to muscle weakness resulting from the loss of their typical origin and the subsequent alteration in load transmission through the fibula.[6-8] Biomechanical studies have demonstrated that even minor alterations in fibular length, such as shortening by 2 mm, can significantly increase tibiotalar joint pressure, leading to compromised ankle stability. Additionally, improper reduction or alignment of the fibula has been shown to reduce the tibial contact area by up to 42%, emphasizing the importance of fibular integrity in preserving normal ankle biomechanics.[9] During the process of weight bearing, the fibula undergoes a distal movement, which deepens the ankle mortise, enhances stability.[10] Furthermore, it has been shown that the load borne by the fibula ranges from 6.4 to 16.7%. Given that the forces transmitted through the leg may reach up to five times an individual's body weight, the fibula makes a significant contribution to bearing these forces.[10] Consequently, it is clearly established that the fibula plays a critical role in both load bearing and the stabilization of the ankle.[10] Prior investigations into fibular head resection have predominantly focused on postoperative knee issues and associated functional outcomes.[3,6,7,11,12] Conversely, there is a limited number of studies in the literature examining the biomechanical changes, stability, and functional outcomes of the foot and ankle following proximal fibula resection.

The presence of clinical signs of ankle instability in patients who have undergone fibula resection may not always correlate with patient discomfort, as some individuals may not perceive these signs as problematic, while others may report instability despite a lack of clinical evidence. Therefore, an accurate clinical assessment by an orthopedic surgeon is crucial in evaluating musculoskeletal pathologies.[13,14] In a systematic review conducted on donor-site morbidity following free fibula flap surgery, pedobarography could be used for objective clinical assessment.[15] Pedobarographic evaluation can be conducted in both static and dynamic modes. The static mode assesses foot balance and load distribution in a stationary position, while the dynamic mode analyzes pressure distribution across the plantar surface throughout the gait cycle, providing insights into functional movement patterns and related parameters.[16]

In the present study, we aimed to evaluate whether changes in ankle radiological parameters following fibular head resection due to tumors led to ankle instability and/or ankle arthritis and to comprehensively assess the impact of resection on clinical outcomes using pedobarographic analysis and pain and function scales.

PATIENTS AND METHODS

Study design and study population

This single-center, retrospective study was conducted at Baltalimani Bone Diseases Training and Research Hospital, Department of Orthopedics and Traumatology between January 2005 and January 2023. Initially, 42 patients who underwent proximal fibula resection for benign aggressive and malignant tumors were screened. Of these, nine were excluded due to Malawer type 2 resection (extensive resection) for malignant tumors and two were excluded due to a history of trauma in the contralateral ankle, which could interfere with normal walking biomechanics and influence comparative analyses. Another patient was also excluded due to permanent foot drop resulting from postoperative peroneal nerve damage, which would significantly affect clinical and biomechanical assessments. Finally, a total of 30 patients (10 males, 20 females; mean age: 33.9±13.8 years; range, 10 to 67 years) who met the inclusion criteria were enrolled. A written informed consent was obtained from each patient. The study was approved by the Baltalimani Bone Diseases Training and Research Hospital Ethics Committee (date: 10.04.2023, no: 50). The study was conducted in accordance with the principles of the Declaration of Helsinki.

Data were collected from medical records, including radiological imaging, clinical examinations, and functional outcome measures that were recorded during routine follow-up visits. Patients who continued their follow-up at our clinic for at least one year after the primary resection, who had suitable radiological and clinical data for evaluation, and who did not have any ankle or knee diseases in both lower extremities that could disrupt walking biomechanics were included in the study. None of the patients received any adjuvant or neoadjuvant treatments such as chemotherapy or radiotherapy. Patients who underwent wide soft tissue resection for malignant tumors or developed permanent foot drop due to peroneal nerve damage after surgery were excluded. The definition of wide resection was based on the criteria for

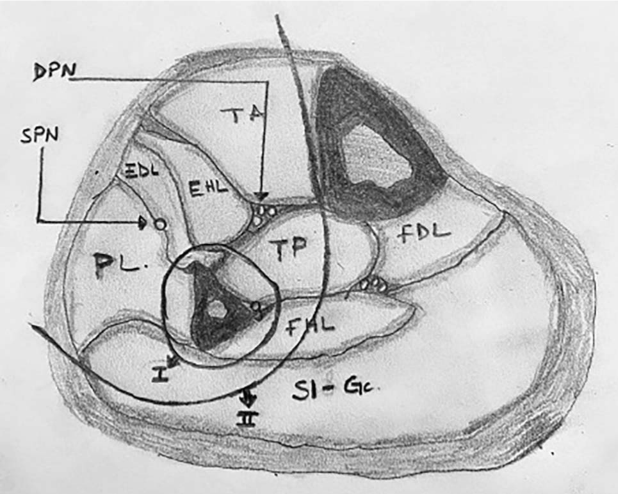

FIGURE 1. Schematic illustration of Malawer type 1 and type 2 resection.

DPN: Deep peroneal nerve; SPN: Superficial peroneal nerve; TA: Tibialis anterior; EDL: Extensor digitorum longus; EHL: Extensor hallucis longus; PL: Peroneus longus; TP: Tibialis posterior; FDL: Flexor digitorum longus; FHL: Flexor hallucis longus; Sl: Soleus; Gc: Gastrocnemius.

type 2 resection described by Malawer in 1984[17] (Figure 1). Type 1 resections involved the removal of the proximal fibula along with 2 to 3 cm of normal diaphysis and a thin cuff of surrounding muscle while preserving the peroneal nerve and its motor branches. The anterior tibial artery was sacrificed only when necessitated by tumor involvement. In contrast, Type 2 resections included the removal of the proximal fibula, 6 to 7 cm of normal diaphysis, the proximal anterior and lateral muscle compartments, the proximal portions of the flexor hallucis longus (FHL) and tibialis posterior (TP) muscles, the anterior tibial artery, the peroneal nerve, and, if required, the peroneal artery. In type 2 resections, the tibiofibular joint was resected extra-articularly, along with a portion of the lateral tibial cortex and metaphysis. All surgeries were performed by senior orthopedic oncologic surgeons with extensive experience in musculoskeletal tumor surgery, ensuring consistency in surgical technique and oncological principles.

Radiological assessment

All measurements were performed using a Picture Archiving and Communication System (Extreme PACS, Ankara, Türkiye). Radiological measurements were conducted by two experienced musculoskeletal orthopedic oncologists, and the average of their measurements was recorded. To comprehensively assess the entire extremity, routine preoperative magnetic resonance imaging (MRI) of the entire cruris (lower leg) was obtained for all patients. Postoperative MRI was also routinely performed during follow-up visits to monitor for tumor recurrence. Of note, despite the proximal resection of the fibula, all radiographic analyses were conducted at the level of the ankle to assess its biomechanical impact. This approach ensured a focused evaluation of ankle-level changes following proximal fibula resection. Additionally, all patients had a normal functioning contralateral limb, which served as a control for comparative analysis.

The measurement techniques are visualized in Figure 1 and were performed as follows:

Anterior tibiofibular distance: Distance between the most anterior point of the incisura and the nearest most anterior point of the fibula was determined by measuring on MRI (Figure 2a).[18]

Posterior tibiofibular distance: Distance between the most posterior point of the incisura and the nearest most posterior point of the fibula was determined by measuring on MRI (Figure 2b).[18]

Fibular rotation: Fibular rotation was determined on MRI using the angle between a line drawn between the anterior and posterior point of the incisura and the line that unites the anterior and posterior fibular tuberosities (Figure 2c).[18]

Talar tilt angle: Talar tilt was determined on by measuring the angle between the tibial distal articular surface and the talar dome surface on a weightbearing anteroposterior radiograph (Figure 2d).[19]

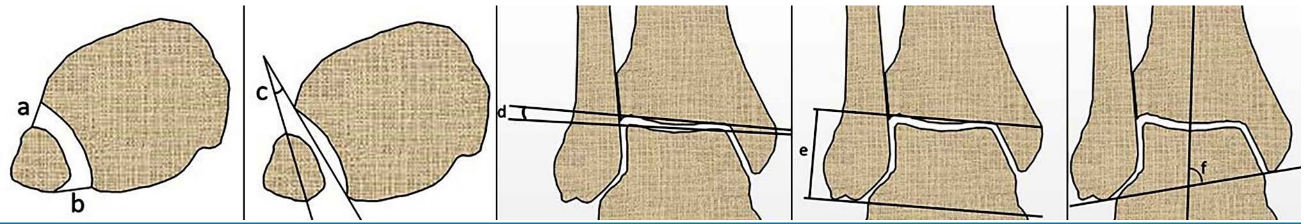

FIGURE 2. Measurements of the ankle; **(a)** Anterior tibiofibular distance, **(b)** posterior tibiofibular distance, **(c)** fibular rotation, **(d)** talar tilt angle, **(e)** fibular length, **(f)** talocrural angle.

Fibular length measurement: Fibular length was measured as the distance from the tip of the lateral malleolus to the distal tibial articular surface on weightbearing anteroposterior radiographs (Figure 2e).[11]

Talocrural angle: Angle was determined by measuring the angle between the line drawn through the tips of both malleoli and the tibial anatomical axis on a weightbearing anteroposterior radiograph (Figure 2f).[19]

Pedobarography

Pedobarographic measurements were obtained using "AS 040 Foot Scan" (Analiz Sistem, İstanbul, Türkiye). For static pedobarographic measurements, participants were asked to stand upright on a special pressure measurement platform. In this position, the plantar pressure distribution of each participant was recorded for 10 sec. The magnitude of pressure distribution was evaluated using the Analiz Sistem Footscan® gait software, and the relative pressure loads (%) were recorded (Figure 3a). Dynamic pedobarographic measurements involved participants walking on the pedobarographic platform at their normal daily walking speeds. To ensure they could maintain their natural walking rhythms, participants performed several trial walks on the platform. Each participant was instructed to maintain their natural walking rhythm while on the platform and to avoid looking at the platform during the walk. In case of any errors, the walk was repeated. Dynamic measurements were recorded for a minimum duration of 60 sec. For a detailed analysis

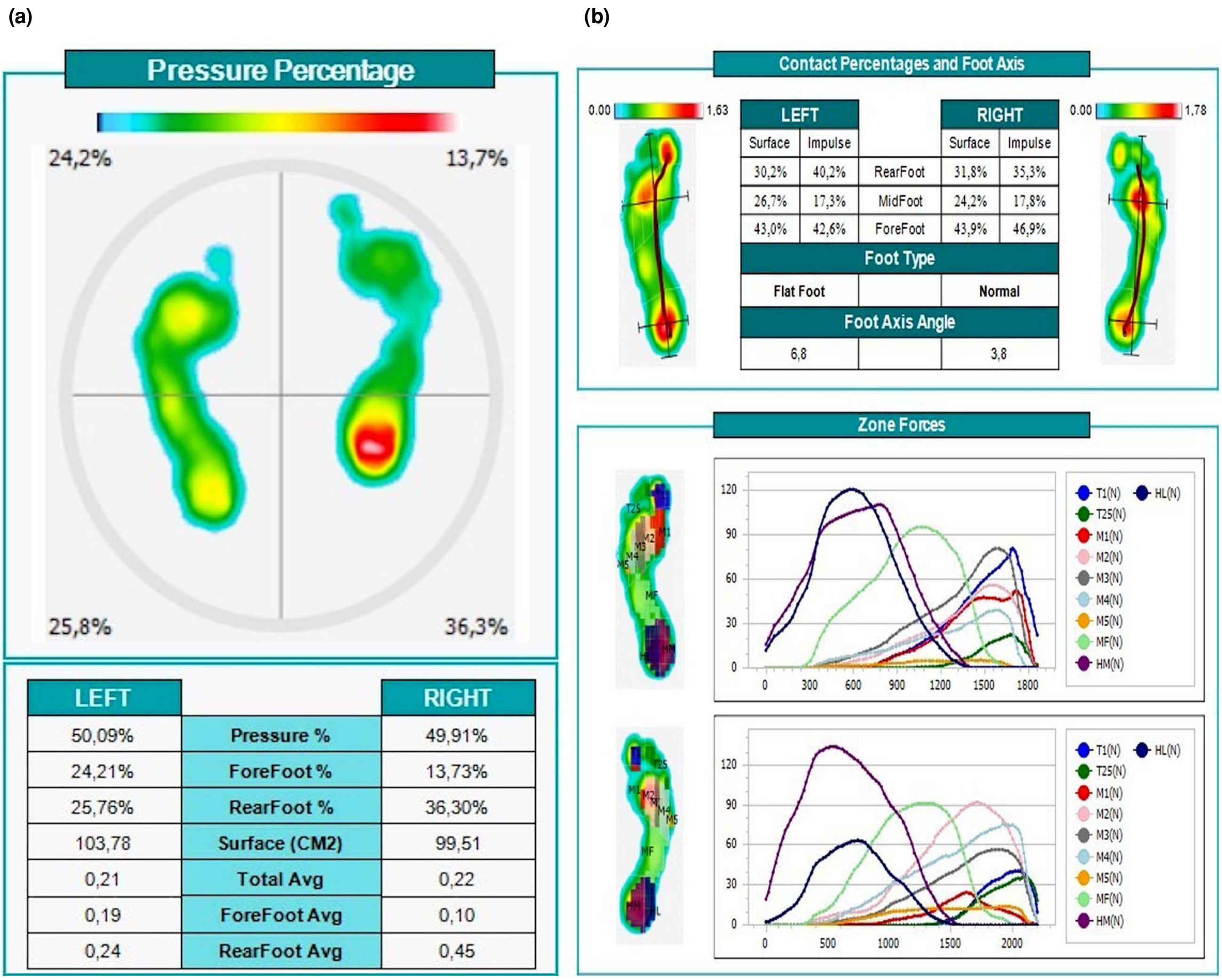

FIGURE 3. (a) Pressure distribution on pedobarography. **(b)** Pedobarographic analysis of contact percentages, foot axis, and zone forces.

of toe loading, the footprints were subdivided according to the manufacturer's guidelines using the Footscan® gait software, and the maximum pressures (N/cm²) were recorded and compared between the operated and contralateral sides for toes 2 to 5 (T2-T5) and the hallux (T1) (Figure 3b).

Data collection

The demographic and clinical information of the patients, including age, sex, surgery site, type of tumors, and duration of follow-up, was retrospectively obtained from the hospital database. Clinical examination included assessment of knee and ankle range of motion, varus, valgus, anteroposterior and rotator instability at the knee, ankle varus and valgus examination sensory or motor loss. Surgical site complications were recorded. Functional outcomes were assessed using the Musculoskeletal Tumor Society (MSTS) scoring system, and clinical outcomes were evaluated through the Visual Analog Scale (VAS) for pain. The MSTS scoring framework evaluates patient-related activities, encompassing aspects such as pain, functionality, emotional acceptance, support mechanisms, ambulatory capabilities, and locomotion patterns. Each of these six domains was appraised using a five-point metric scale, culminating in a comprehensive maximum attainable score of 30 points.[20]

Statistical analysis

Statistical analysis was performed using the IBM SPSS version 22.0 software (IBM Corp., Armonk, NY, USA). Continuous variables were expressed in mean ± standard deviation (SD) or median (min-max), while categorical variables were expressed in number and frequency. The independent t-test was conducted to compare continuous variables between subgroups. Pearson correlation analysis was performed to identify significant associations between the percentage of fibular resection and changes in radiological or clinical parameters. Subgroup analyses were conducted to examine potential interactions between the extent of fibular resection and outcome measures. Sensitivity analyses were performed by repeating key statistical tests after excluding outliers to ensure robustness and reliability of results. Missing data were addressed by retrieving additional information from hospital records when available or excluding incomplete cases from specific analyses. Only patients with complete data for major outcome variables were included in the primary analysis. To manage potential bias from loss to follow-up, only patients with at least one year of documented follow-up were considered in the final dataset. A p value of <0.05 was considered statistically significant.

RESULTS

The mean follow-up was 82.6±51.9 (range, 14 to 225) months. The most common histopathological diagnosis was an atypical chondroid tumor in 10, followed by a GCTB in nine, a chondrosarcoma in five, an aneurysmal bone cyst in five, and an osteochondroma in one patient. The majority of the operations were performed on the dominant side (n=17). The mean VAS score was 1.5±1.4 (range, 0 to 4) and the mean MSTS score was 26.8±2.9 (range, 20 to 30). Ankle radiographs and MRI scans were compared between the operated and unaffected sides (Table I).

The analysis of load balance (%) and T2-5 max pressure (N/cm²) between the operated side (n=30) and the unaffected side (n=30) revealed significant differences (p<0.001, p=0.007) (Table II).

The mean percentage of resected fibula was 24.4±6.7% (range, 15.5 to 43.8%). There was a positive correlation between the percentage of

TABLE I
Comparison of radiological measurements between operated and unaffected sides

	Operated side (n=30)	Unaffected side (n=30)	
	Mean±SD	Mean±SD	*p*
Fibular length (mm)	26.1±2.1	27.4±2.3	<0.001*
Talar tilt (degree)	0.9±0.4	0.6±0.4	<0.001*
Talocrural angle (degree)	78.9±1.9	78.6±2.1	0.006*
Fibular rotation (degree)	10.6±5.8	14.2±5.6	<0.001*
Anterior tibiofibular distance (mm)	4.2±0.7	4.2 ±0.7	0.084
Posterior tibiofibular distance (mm)	7.5±1.6	7.7±1.3	<0.001*

SD: Standard deviation; * p<0.05.

TABLE II

Comparison of load balance, toes push-up forces and foot axis angle between operated and unaffected sides

	Operated side (n=30)	Unaffected side (n=30)	
	Mean±SD	Mean±SD	*p*
Load balance (%)	47.7±5.8	52.3±5.8	<0.001*
T1 max pressure (N/cm²)	49.8±26.9	64.1±29.4	0.857
T2-5 max pressure (N/cm²)	31±22.1	43.3±18.8	0.007*
Foot axis angle	4±4.8	4.1±8.4	0.587

SD: Standard deviation; * p<0.05.

resected fibula and differences in fibular rotation (r=0.67, p<0.001), fibular length (r=0.73, p<0.001), talocrural angle (r=0.49, p=0.003), and talar tilt angle (r=0.66, p<0.001) (Figure 4, and 5a, b). Particularly in patients with more than 30% resection, this correlation was even more pronounced. The correlation analysis also showed that the MSTS score had weak negative correlations with

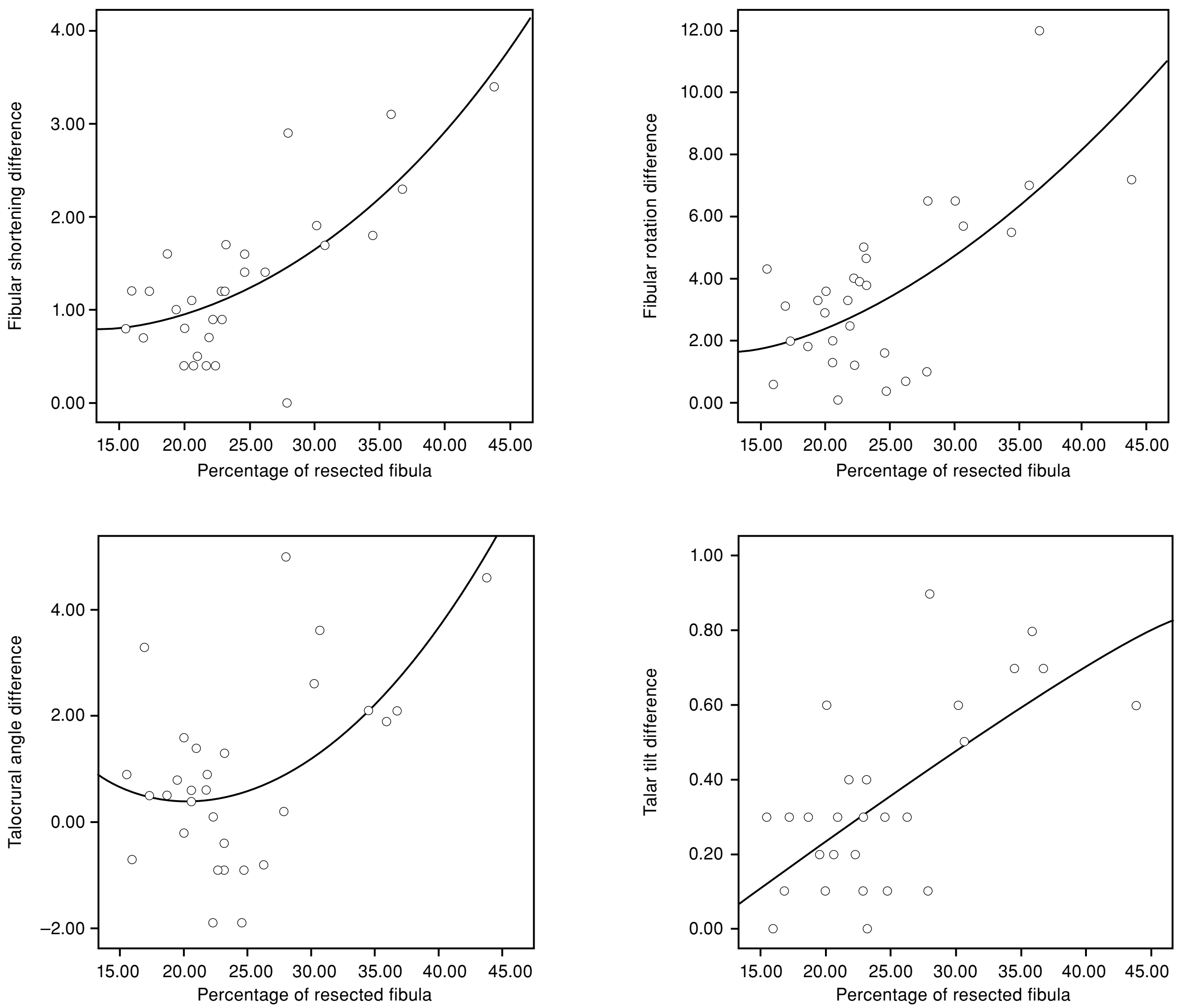

FIGURE 4. Correlation between the percentage of resected fibula and changes in ankle radiological parameters.

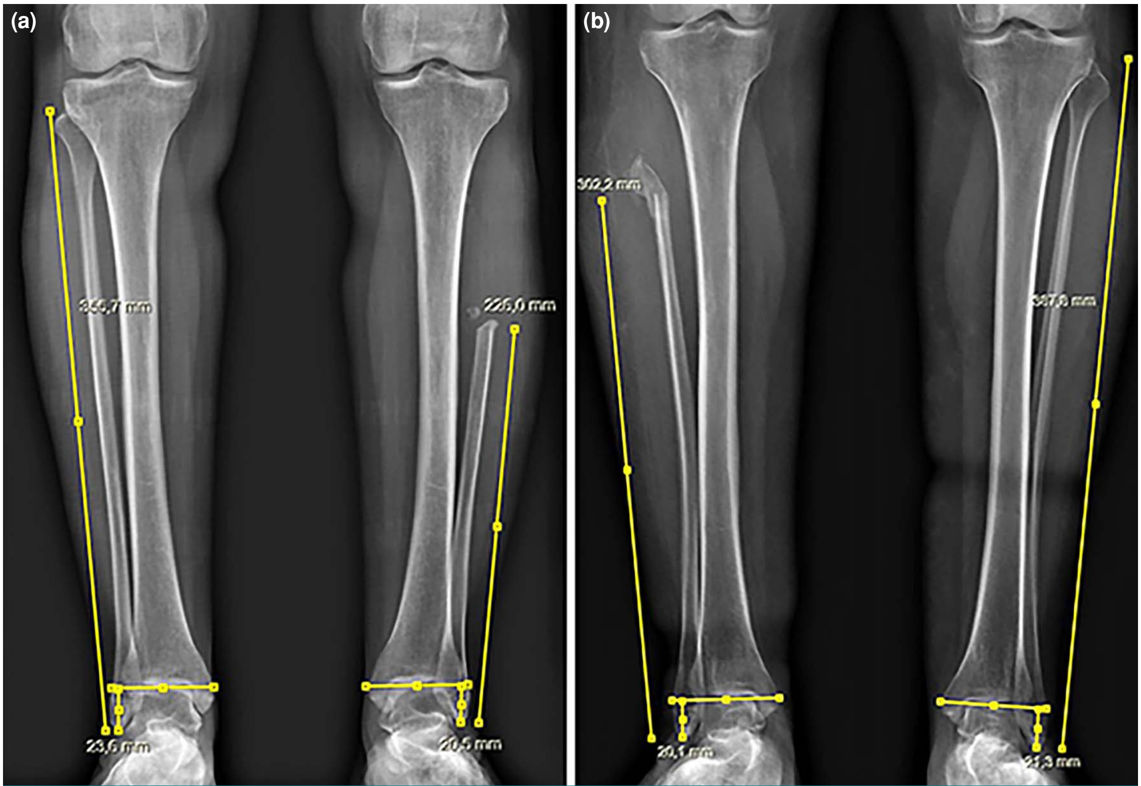

FIGURE 5. Postoperative radiograph examples of proximal fibula resection. **(a)** 37% resected fibula 3.1 mm fibular length difference, **(b)** 22% resected fibula- 1.2 mm fibular length difference.

differences in fibular length, fibular rotation, talar tilt, and talocrural angle, none of which reached statistical significance. In contrast, the VAS score demonstrated a significant positive correlation with fibular length difference (r=0.45, p=0.01), while its correlations with other parameters were not statistically significant (Table III).

DISCUSSION

In the present study, we evaluate changes in ankle radiological parameters following fibular head resection due to tumors in terms of ankle instability and/or ankle arthritis and assessed the impact of resection on clinical outcomes. The main findings

TABLE III
Correlation between the percentage of resected fibula, MSTS, VAS, and differences in ankle radiological parameters

	Fibular length difference	Fibular rotation difference	Talar tilt difference	Talocrural angle difference
MSTS				
r	–0.35	–0.3	–0.1	–0.1
p	0.06	0.1	0.62	0.61
VAS				
r	0.45*	0.34	0.17	0.1
p	0.01	0.06	0.36	0.58
Resected fibula (%)				
r	0.67*	0.73*	0.66*	0.49*
p	<0.001	<0.001	<0.001	0.003

MSTS: Musculoskeletal Tumor Society; VAS: Visual Analog Scale; r: Pearson correlation; * p<0.05.

of this study are that proximal fibula resection caused significant changes in ankle radiological measurements such as fibular length, talar tilt, talocrural angle, and fibular rotation. The positive correlation of these values with the increase in fibular resection was remarkable. Additionally, in pedobarographic measurements, the load balance was disrupted in favor of the unaffected side. Despite these changes, the MSTS score was not significantly low, and clinically good results were achieved. The VAS scores of the patients at the final follow-up revealed that they were able to continue their lives pain-free or with minimal pain.

The fibula plays a vital role in the stability and load distribution of the ankle joint complex.[10] Fibular shortening can lead to altered biomechanics and abnormal stress on the articular surfaces, potentially contributing to the development of ankle osteoarthritis.[21] It has been demonstrated that 2 mm of fibular shortening increases the peak pressures on the talus cartilage by 33% and caused an 8% reduction in tibiotalar contact area.[22] In a study, the most common cause of ankle pain and the development of osteoarthritis following malunion of a fibular fracture was identified as fibular shortening, and 25 out of 31 patients were treated with fibular lengthening.[23] In our study, the measured fibular length was significantly lower on the operated side, and this reduction was positively correlated with the percentage of fibular resection. In resections over 30%, the reduction exceeded 2 mm. Although we did not encounter significant osteoarthritis findings or ankle instability in our study which may be due to the relatively small sample size, we believe that it is necessary to be cautious with increasing amounts of resection. To address potential instability, surgical techniques such as fibular fixation to the tibia or syndesmotic fusion can be considered. Future studies should evaluate whether these interventions can prevent distal fibular displacement and associated ankle instability.

In a study assessing syndesmotic malreduction following rotational ankle fractures, postoperative measurements on the injured side showed an anterior tibiofibular distance that was 1.34±1.05 mm greater and a posterior tibiofibular distance that was 1.81±1.41 mm greater compared to the healthy side.[24] Additionally, the mean fibular rotation was measured to be 5.75±4.30 degrees lower on the injured side. However, it was reported that these changes did not significantly affect clinical outcomes at the one-year follow-up. In a biomechanical cadaver study, it was reported that while the contact pressure in the tibiofibular and talofibular joints minimally increased with plantarflexion and a slight internal rotation of 5 degrees, the pressures in both joints significantly increased with an internal rotation of 10 degrees.[25] In our study, it is noteworthy that as the length of fibular resection increases, the internal rotation correspondingly increases. We believe that our study may provide guidance in considering these factors in the postoperative follow-up of patients who have undergone proximal fibular resection, particularly concerning potential ankle issues.

The fibula forms a frame structure with the tibia, connected proximally and distally by anterior and posterior tibiofibular ligaments. This dynamic box-frame structure strengthens the lateral stability of the ankle joint. A proximal 3-cm cut in the fibula is sufficient to significantly increase the inversion angle of the ankle, and sequential cuts from the proximal 3-cm position to the distal 6-cm position result in a gradual but non-significant increase in instability. Therefore, the head of the fibula appears to be essential for the stabilization of the ankle joint complex.[21] Our study extends these findings by demonstrating that proximal fibula resection can lead to significant changes in ankle radiological measurements, although these changes do not necessarily translate into clinical instability.

Pedobarographic analysis is an important tool in objectively evaluating the load-bearing mechanism of the lower extremity and postoperative functional changes.[13,16] In our study, pedobarographic analysis revealed that load distribution was significantly lower on the operated side compared to the healthy side ($p<0.001$), and the maximum pressure values, evaluated as the push-up strength of the T2-T5 toes, were significantly reduced ($p=0.007$). These changes may be associated with factors such as postoperative muscle weakness, altered biomechanics, impaired ankle stability, or patients' conscious or unconscious attempts to avoid loading the operated limb. In particular, the detachment of the extensor digitorum longus and peroneus longus muscles, which originate from the proximal fibula, during surgery may contribute to reduced push-off strength in the smaller toes and alterations in pressure distribution. Indeed, in a study, it was emphasized that the muscle strength on the operated side was lower and this decrease could be due to the muscles separated from their attachment sites on the fibula.[26] In the literature, study on donor site morbidity following resection of the fibula gait analysis of the donor leg and the contralateral normal leg showed definite differences, which could be attributed to weakness of the deep muscles caused by loss of their normal origin and to the change in load transmission through the fibula.[8] These findings highlight the need for rehabilitation strategies to retrain load distribution during the rehabilitation process.

Nonetheless, our study has several limitations. Although the follow-up period was sufficiently long, the retrospective nature of the study and the relatively small sample size may limit the generalizability of the findings. Additionally, while our measurements were precise, the potential for inter-observer variability in radiological assessments remains a concern. Future studies with larger sample sizes are needed to validate our findings and further explore the detailed mechanisms behind the observed changes in ankle function and stability.

In conclusion, proximal fibula resection for tumors involving the fibular head leads to significant changes in ankle radiological measurements and load distribution. In our study, fibular length and fibular rotation were significantly reduced, while talar tilt and talocrural angle were increased on the operated side. Additionally, there was a positive correlation between the percentage of fibular resection and alterations in fibular rotation, fibular length, talocrural angle, and talar tilt angle, with more pronounced changes observed in resections exceeding 30%. Despite these changes, clinical outcomes as measured by MSTS scores were usually favorable, and the low VAS scores indicated minimal pain levels. These findings underscore the importance of comprehensive postoperative care, including targeted rehabilitation to address potential biomechanical alterations and ensure optimal functional recovery.

Data Sharing Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions: Concept, design, literature review, writing the article: N.İ.; Data collection, analysis: A.K.; Idea/concept, control/supervision, critical review: O.E.A.; Idea/concept, data collection, control/supervision: M.C.A.; Data collection, materials: T.B.

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