Kinetic and Kinematic Analysis of Gait in Type IV Osteogenesis Imperfecta Patients: A Comparative Study

Abstract

Background: Osteogenesis imperfecta (OI) is a genetic connective tissue disorder characterized by skeletal deformity and increased risk of fracture. Independent mobility is of concern for OI patients as it is associated with the quality of life. The present study investigates the variation of kinetic and kinematic gait parameters of type IV OI subjects and compares them with age-matched healthy subjects. **Materials and Methods:** Gait analysis is performed on five type IV OI patients and six age-matched normal subjects. Spatiotemporal, kinematic, and kinetic data are obtained using Helen Hayes marker placement protocol. **Results:** The results indicate an imprecise double-humped profile for vertical ground reaction force (GRF) with reduced ankle push off power and walking speed for OI subjects. Moreover, a comparison of vertical GRFs in OI subjects with that of healthy subjects suggests lower values for the former. The results encourage and motivate for further investigation with a bigger set of subjects. **Conclusion:** This information may be useful in developing a better understanding of pathological gait in type IV OI subjects, which ultimately helps the design of subject-specific implants, surgical preplanning, and rehabilitation.

Keywords: *Brittle bone disease, gait analysis, kinematics, kinetics, osteogenesis imperfecta*

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Introduction

Osteogenesis imperfecta (OI) is a congenital disorder that affects the musculoskeletal system.[1] Patients suffering from OI have deformed and fragile bones, muscle weakness, and ligamentous laxity as major musculoskeletal complications.[2,3] OI is caused by mutation in *COL1A1* and *COL1A2* genes which encode for α1(I) and α2(I) chains of type I collagen, which is the most abundant protein in bone, skin, and tendon extracellular matrix.[2,3] OI is a rare disorder with chances of approximately 1 in 15,000–20,000 births.[3] In 1979, Sillence and Rimoin classified OI broadly into four types by inheritance, clinical, and radiological features.[1] The severity of the type was based on the mutation altering the collagen structure such as type I being mild, type II being lethal, type III being severe, and type IV being moderate.[1,4] Currently, there is no cure for OI, but bisphosphonates are used as pharmacological interventions which enhance the bone mass.[5-10] Intramedullary nailing is widely used for correcting the skeletal deformity and as a preventive measure for fractures in long bones in OI.[11-13] Independent mobility of OI patients is a major concern as it affects the quality of life. Qualitative studies on patients with OI are available in the literature to understand patients' physical, emotional, and social aspects of life.[14-16] Gait is one of the quantitative methods of analyzing the mobility and thus may also help in preoperative planning of the intervention.[17-20] Limited studies in the literature presented quantitative knowledge on the gait in patients with OI. To our knowledge, there are specifically two studies on gait analysis of type I OI patients which are available in the literature.[21,22] A recent study of quantitative gait analysis for one type IV OI patient is also available in the literature.[23] There is limited knowledge about the gait characteristics of OI patients specifically type IV OI patients such as step length, cadence, velocity, ground reaction forces (GRFs), and joint reaction forces. This study aims to improve the existing knowledge on type IV OI gait and thus presents a quantitative comparison of type IV OI gait with age-matched controls. The data collected here are a part of a broader study to understand loading

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environment of lower limbs in OI patients which would be further used in preoperative and surgical planning, design, and modification of OI implants. This study helps in improving the existing knowledge of gait characteristics of OI type IV patients and also in improving the current treatment strategies. This certainly improves the quality of life of OI patients.

Materials and Methods

Eleven ambulatory children are included in this study: five type IV OI patients (age 7.8 ± 1.79 years, 108.6 ± 9.86 cm) and six healthy subjects (9 ± 1.79 years, 132.75 ± 5.36 cm). All the subjects are community ambulators without assistive devices. Healthy subjects are selected based on the criterion that they had no previous history of musculoskeletal problems and had lower body mass index than the normal range to mimic OI subjects. Type IV OI subtype was confirmed from the clinical and genetic analysis. Patients with other disease and aged under 5 years are excluded. All the patients have surgical intervention at least 6 months before the gait analysis and have no deformity in long bones as revealed by physical and X-rays examination. OI subjects with similar symptoms and musculoskeletal complications were included in this study to address the effect of heterogeneity as shown in Table 1. The testing protocol for both patients and healthy subjects was approved by the Institute Ethics Committee of the institution. Written informed consent is obtained from all the participants or legal representatives. Gait analysis is performed on the selected children at the Gait Analysis Laboratory in the Department of Physical and Rehabilitation Medicine. The marker placement and anthropometric measurements for all the subjects are done by the same person. Instrumented gait analysis is performed using BTS GAITLAB (BTS Bioengineering, Italy) system with six infrared cameras (500 Hz) and 16 force plates (1000 Hz). The system is used to acquire both kinematic and kinetic data. Three-dimensional kinematic data are recorded with the help of 18 reflective infrared markers using Helen Hayes protocol. The floor-mounted force plates are used to acquire the kinetic data. The subjects walked at a self-selected speed. The hip, knee, and ankle angles in sagittal, frontal, and transverse planes are obtained from the kinematic data. The kinetic data recorded were GRFs in sagittal, frontal, and transverse planes. Joint reaction forces and moments are calculated from kinetic data using a rigid body model and the principles of inverse dynamics. The forces are expressed as percentage body weight whereas gait cycle was expressed in percentage gait cycle. To evaluate the difference between OI and normal groups, Welch's *t*-test was used with a significance level of 0.05.

Results

The anthropometric data show that OI patients had smaller stature as compared to control subjects [Table 2]. The kinematic data analysis revealed that the OI subjects walk with lower velocity as compared to the controls as shown in Table 3. The kinematic data also revealed that the stride length and step length for the OI group are shorter than that of normal subjects. Contrary to this, the step width is somewhat wider in OI subjects compared to that of healthy subjects.

Kinematic analysis showed the variation of ankle, knee, and hip angles throughout the gait cycle for both the groups [Figure 1]. Figure 1a-c shows the ankle, knee, and hip flexion extension angles, respectively. In Figure 1a, the OI group has reduced plantar flexion angle in swing phase and increased dorsiflexion in stance phase as compared to the age-matched healthy group. Similarly, Figure 1b shows

Table 1: Clinical and surgical history for osteogenesis imperfecta subjects

Parameter	Subject 1	Subject 2	Subject 3	Subject 4	Subject 5
Gender	Female	Male	Male	Male	Male
Joint laxity	Yes	No	No	Yes	No
Fractures					
History of lower limb fractures	6	4	4	3	6
Time since last fracture (months)	10	28	19	22	13
Total number of surgeries	2	1	1	NA	2
Lower limb nailing	Right femur (intramedullary nail) Left femur (intramedullary nail)	Both femur (intramedullary nail)	Left femur (intramedullary nail)	No	Both femur (intramedullary nail)
Time since last surgery (months)	10	26	Left tibia (intramedullary nail) 14	NA	13
Pelvic obliquity (°)	Yes (6)	Yes (5)	No	Yes (4)	No
Spinal deformity (°)	Thoracic curve (14)	No	No	No	No

NA=Not available

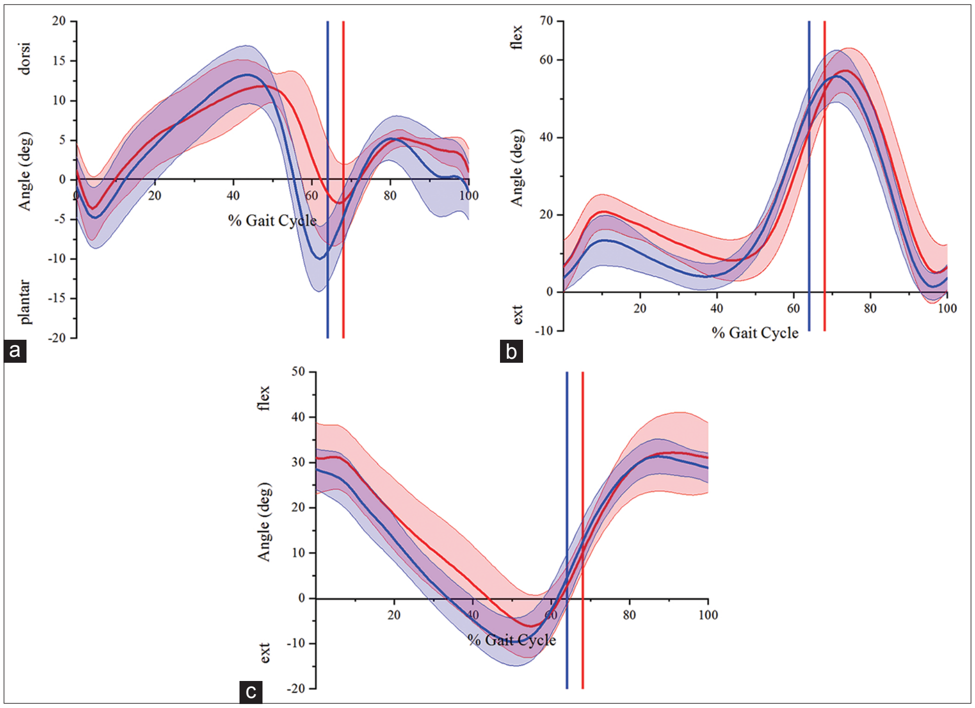

Figure 1: Flexion extension angle for OI (red band representing mean ± SD with red vertical line representing toe off) and healthy subjects (blue band representing mean ± SD with blue vertical line as toe off) for (a) ankle, (b) knee, and (c) hip (dorsi indicates dorsiflexion, plantar indicates plantar flexion, flex indicates flexion and ext indicates extension). OI=Osteogenesis imperfecta, SD=Standard deviation

Table 2: Anthropometric details of osteogenesis imperfecta and control (healthy) subjects (mean±standard deviation)

Subjects	Age (years)	Height (cm)	BMI
OI	7.80±1.79	108.60±9.86	11.83±0.85
Control	9.00±1.79	132.75±5.36	14.69±2.57

OI=Osteogenesis imperfecta, BMI=Body mass index

Table 3: Spatiotemporal parameters for osteogenesis imperfecta and normal subjects (mean±standard deviation)

Parameter	OI	Control	*P*
Velocity (percentage height/s)	66.97±9.59	82.65±10.49	**0.0297**
Velocity (m/s)	0.72±0.13	1.07±0.10	**0.0015**
Step width (m)	0.14±0.03	0.13±0.02	0.3028
Stride length (m)			
Left	0.72±0.19	1.06±0.08	**0.0131**
Right	0.74±0.17	1.05±0.09	**0.0105**
Step length (m)			
Left	0.37±0.08	0.53±0.05	**0.0076**
Right	0.36±0.09	0.53±0.03	**0.0139**
Double-support phase (%)			
Left	9.15±1.26	7.97±1.02	0.1312
Right	11.00±2.29	8.07±0.94	**0.0429**

P values in bold indicate OI group is significantly different from normal with $P<0.05$. OI=Osteogenesis imperfecta

the increased hyperextension of knee in the midstance phase and Figure 1c depicts the increased hip flexion angle in midstance phase for OI group.

Kinetic analysis revealed the variation of GRFs, joint torques, and ankle push off power for both the groups [Figures 2-4]. Figure 2a-c respectively compares the vertical, longitudinal, and lateral GRFs experienced by OI and control subjects. Figure 2a indicates the imprecise double-humped profile as well as reduced maximum mean value for OI group. Apart from this, it is evident from Figure 2a that the OI subjects have delayed foot off as compared to healthy subjects. Figure 2b shows reduced mean longitudinal GRF for OI group, whereas Figure 2c represents increased medial-lateral force in the OI group with respect to that of control (i.e., normal) group. Figures 3a-c represents the ankle, knee, and hip flexion extension torques, respectively. Figure 3a and b shows the reduced torque in OI group compared to the healthy group for ankle and knee, respectively. Figure 3c shows the increased torque for hip in case of OI group. It seems possible that this compensates for the reduced torques corresponding to ankle and knee. Figure 4 shows the reduced ankle push off power for OI group compared to that for the healthy group.

Discussion

This study quantitatively compares the gait characteristics of type IV OI patients with age-matched control subjects. The temporal, kinematic, and kinetic parameters for lower limbs have been studied in the present work. These parameters will be useful for the clinical as well as surgical decision-making. For example, the knowledge of kinematic parameters help design better rehabilitation programs,

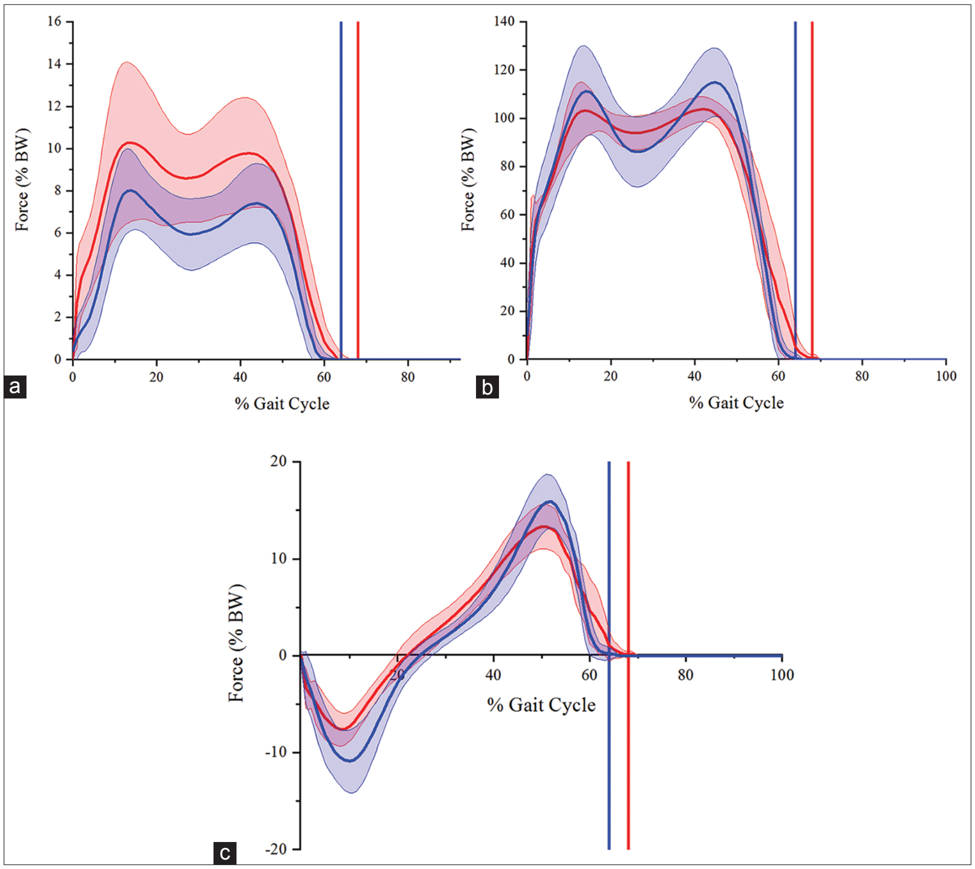

Figure 2: Ground reaction forces for OI (red band representing mean ± SD with red vertical line as toe off) and healthy subjects (blue band representing mean ± SD with blue vertical line as toe off) for (a) vertical ground reaction force, (b) anterior-posterior ground reaction force, and (c) medial-lateral ground reaction force. OI=Osteogenesis imperfecta, SD=Standard deviation

and the kinetic parameters help in designing subject-specific implants or prosthesis. Graf *et al*.[21] performed the quantitative gait analysis of ten OI type I adolescents and reported deviations in kinematic and kinetic parameters in comparison with typically developing children. They reported the abnormality in type I OI gait in terms of increased double support, delayed foot off, and reduced ankle power during push off. The present study also showed an increase in double support for type IV OI subjects compared with healthy subjects [Table 3]. The results also presented the reduced ankle push off power for OI subjects [Figure 4]. This reduction in power may be attributed to decrease in muscle strength as joint laxity was absent in the subjects [Table 1]. However, the muscle power in the subjects was not assessed for the present study, to avoid any accidental fracture. Reduced velocity in OI subjects also contribute to the decreased power generation as it has been reported in literature that shorter subjects have reduced velocity.[24] Garman *et al*.[22] also reported quantitative gait analysis with a large sample of 40 type I OI patients and compared them with age-matched typically developing children. Apart from the parameters reported in the Graf *et al*.[21] and Garman *et al*.,[22] the present study also provides the comparison of GRFs. These forces can be utilized to calculate joint reaction forces and moments at the knee and hip joints along with the calculation of muscle forces using the principles of inverse dynamics and static optimization respectively. These forces and moments play an important role in the estimation of mechanical environment (i.e., forces and moments) to which the implant is subjected to and thus provide the valuable information to be used by the design engineers for better and reliable design of implants. Moreover, GRFs also provide information about the loading rates (impact forces), which may aid in improvement of existing medical equipment such as implants and orthosis with respect to such loading scenarios.

The kinematic results [Figure 1a-c] explains the differences in both the groups and the results are consistent with the findings of Graf *et al*.[23] This quantitative information about range of motion helps clinicians and physiotherapists to design better rehabilitation and exercise programs for the patients. In addition, this information can be utilized by the surgeons and interdisciplinary team involved in the management and treatment of OI patients.

The kinetic parameters specifically GRFs [Figure 2a-c] will be useful for designing subject-specific surgical interventions as well as implants or prosthesis. These forces provide quantitative information about the role of each

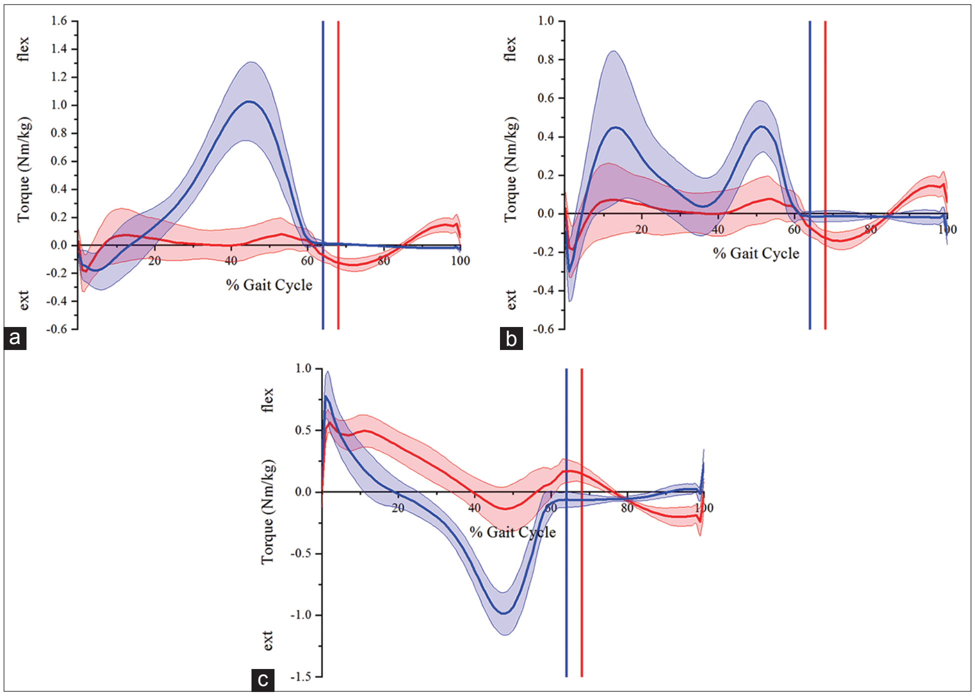

Figure 3: Flexion extension torque for OI (red band representing mean ± SD with red vertical line as toe off) and healthy subjects (blue band representing mean ± SD with blue vertical line as toe off) for (a) ankle, (b) knee, and (c) hip (flex indicates flexion and ext indicates extension). OI=Osteogenesis imperfecta, SD=Standard deviation

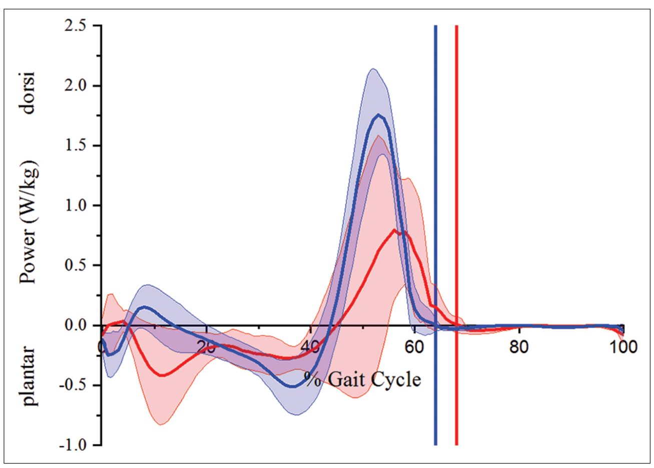

Figure 4: Ankle flexion extension power for OI (red band representing mean ± SD with red vertical line as toe off) and healthy subjects (blue band representing mean ± SD with blue vertical line as toe off) (dorsi indicates dorsiflexion and plantar indicates plantar flexion). OI=Osteogenesis imperfecta, SD=Standard deviation

limb in postural control and also about load distribution of the subjects during the gait cycle.

The ankle, knee, and hip flexion extension torque [Figure 3a-c, respectively] can be used for better understanding of kinetics of OI subjects in comparison to healthy subjects. The findings of reduced ankle push off power for OI group compared to healthy group [Figure 4] are aligned with that in the literature, viz., Graf *et al.* and Garman *et al.*[21-23] Although the number of subjects is too small to ascertain the effects of heterogeneous nature of type IV OI patients, the present results explain the gait characteristics of type IV OI subjects, which are consistent with the gait characteristics of type I OI subjects reported in the literature.[21,22] The information provided in the present study is important in clinical setting as it helps the clinicians, surgeons, and physiotherapists to effectively preplan the surgical intervention and rehabilitation for individual. Besides, the knowledge of subject-specific forces also helps in designing subject-specific implants and physical exercises. Although implants do not improve the walking ability, they provide structural support to the fragile bones in OI subjects with degraded mechanical properties. This helps in increasing ambulatory potential, decreasing number of fractures, and improving their quality of life.

The parameters reported in the present study are crucial for understanding the gait of type IV OI subjects. They also serve as input for musculoskeletal modeling which will be useful for predicting subject-specific muscle and joint contact forces.[25] The findings in terms of kinematic and kinetic parameters for type IV OI subjects can also be utilized by clinicians for preoperative planning, surgical intervention, and rehabilitation for better results and for improving the quality of life of patients.

Conclusion

Spatiotemporal distribution of kinematic and kinetic parameters is presented in this study. These parameters provide insight into pathological gait of the patients with type IV OI and help clinicians to decide the rehabilitation and surgical interventions for them. The presence of wide variability in different forms of OI as well as in individuals with the same type also, the subject-specific intervention will result in improved quality of life for the patients. The GRFs for individual patients can be utilized to predict the joint contact forces using the principles of inverse dynamics which can further help in designing subject-specific implants. The knowledge of these joint contact forces along with the range of motion depicted by kinematic parameters helps in designing subject-specific exercise programs for improving the quality of life of a patient. The quantitative knowledge of gait characteristics including kinematics and kinetics assists the clinicians to optimally design the rehabilitation program for these patients and also help in surgical decision-making. A limitation of the present study is that the number of subjects for both the groups is small. Future research with a large number of subjects might provide more insight into the gait characteristics of type IV OI subjects in comparison with the healthy subjects.

Declaration of patient consent

The authors certify that they have obtained all appropriate patient consent forms. In the form, the patients have given their consent for their images and other clinical information to be reported in the journal. The patients understand that their names and initials will not be published and due efforts will be made to conceal their identity, but anonymity cannot be guaranteed.

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Conflicts of interest

There are no conflicts of interest.

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