Research Paper

Evaluation of Lower Limb Angular Acceleration in Healthy and Hallux Valgus Young and Older Women During Gait

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Citation Sardary S, Tabatabai Ghomsheh F, Norouzi HR, Fatahi A. Evaluation of Lower Limb Angular Acceleration in Healthy and Hallux Valgus Young and Older Women During Gait. Iranian Rehabilitation Journal. 2024; 22(4):691-700. http://dx.doi.org/10.32598/irj.22.4.2180.1

http://dx.doi.org/10.32598/irj.22.4.2180.1

Article info:
Received: 13 Sep 2023
Accepted: 28 Jan 2024
Available Online: 01 Dec 2024

ABSTRACT

Objectives: To comprehend the kinematic effects of hallux valgus (HV) deformity on young and older people, we assessed the angular acceleration of the joints in the lower limbs of these women.

Methods: Forty-eight women in two groups, young adults (20-30 years old) and older adults (50-60 years old), participated in this study (12 healthy and 12 with HV). We used an inertial measurement unit (IMU)-based motion capture system to measure the kinematics of motion. Biomechanical variables were assessed at an ideal speed during gait (stance and swing phases). All modules were calibrated in advance and then attached to the right thigh, shank, and foot.

Results: The results showed that in the young group, angular acceleration was significantly different during gait in all planes of the ankle joint, the sagittal plane of the knee joint, and the horizontal and frontal planes of the hip joint. In the older group, it was significantly different in the sagittal plane of the ankle and knee and the sagittal and frontal planes of the hip joint.

Discussion: It appears that the angular acceleration of the lower limb joints was affected by HV, especially in the young group. Additionally, the angular acceleration of the knee joint was less affected in both groups.

Keywords:

Hallux valgus (HV), Angular acceleration, Lower limb, Gait, Older women

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Highlights

- Angular acceleration of the ankle joint in all planes was significantly affected by hallux valgus (HV) in young women, while only the frontal plane was affected in older women.

- Significant differences in knee joint angular acceleration were observed in the frontal and horizontal planes between young, healthy women and those with HV and in the frontal plane of the knee joint in older individuals.

- HV affected the angular acceleration of the knee joint in the horizontal and sagittal planes in young women and the frontal and sagittal planes of the knee joint in older women.

- Angular acceleration diagrams of older women with HV exhibited a noisy behavior pattern.

Plain Language Summary

HV is a common and progressive deformity that primarily affects women. This condition significantly decreases the quality of life (QoL), especially among older people. However, the relationship between HV and the kinematic parameters of lower limb joints has not been extensively studied. This research compared the angular acceleration of lower limb joints during gait in 48 young and older women, including healthy individuals and those with HV. The findings indicate that HV significantly affected the angular acceleration of lower limb joints, particularly in the young age group. Interestingly, older women with HV displayed a pattern of noisy behavior in their angular acceleration.

Introduction

Hallux valgus (HV) is a frequently occurring deformity known for its progressive nature. This deformity is characterized by a lateral deviation of the hallux, the big toe, and a medial deviation of the first metatarsal bone from the body's midline. It is important to note that the deviation must be 15 degrees or greater for the condition to be classified as HV [1-4]. It is a foot deformity with high prevalence among older women. The condition is more frequently observed in females, with a reported prevalence ranging from 30% to 58%, compared to males, whose reported prevalence is 13% to 25%. Also, HV affects approximately one in three individuals aged 65 or older [5-8]. The prevalence of HV has been reported to be 28.4% in young adults and can reach up to 74% in older adults, according to various studies [7, 9]. HV is influenced by multiple factors, including genetic predisposition, foot structure, sex, age, and footwear [10]. The likelihood of developing HV is heightened in individuals with congenitally bent big toe joints or flat feet, as noted by some studies [3, 10, 11]. A reduction in the height of the transverse arch and deformation of the flexors and extensors tendon in the big toe typically accompanies the HV deformity. Additionally, the forefoot's width often increases, leading to an altered pressure distribution under the metatarsal heads [2, 6, 12]. Several studies suggest that this deformity has a negative impact on the quality of life (QoL), particularly in older individuals [13-15]. Moreover, it can adversely affect foot posture, gait function, balance, and other lower extremity joints, increasing the risk of falls [2, 6, 7, 13, 15-17].

The metatarsophalangeal joint (MTPJ) in the first toe plays a key role in transferring body weight during the late stance phase of gait. The gradual subluxation of the first MTPJ in individuals with HV could potentially interfere with proper toe-off, leading to altered plantar pressures [15]. Numerous studies have reported altered plantar pressures in individuals with HV, which may reduce adult push-off effort [18, 19]. This condition, in turn, is associated with a change in plantar pressure distribution in the forefoot and reduced motion at the metatarsophalangeal and ankle joints [5, 20, 21]. As a result, the weight-bearing reduction on the big toe during gait may lead to increased pressure under the other toes, causing pain under the little toe. Several studies have reported that HV may lead to knee osteoarthritis and foot pain, which could significantly impact an individual's overall QoL [6, 10, 22, 23].

Older individuals exhibit a decline in their toe flexor muscle strength of 27%-36% compared to their younger peers. This decrease in toe flexor strength may have a major impact on the ability of older adults to walk safely [3, 4, 8]. An individual's toes are in contact with

Sardary S, et al. Lower limb Angular Acceleration in Healthy and HV Women During Gait. IRJ. 2024; 22(4):691-700.

the ground for approximately 75% of the stance phase during walking, and the long toe flexor muscles play a significant role in controlling the forward progression of the leg over the foot [6]. This aspect is critical when individuals must take corrective steps to maintain balance in a near-fall scenario. It has been reported that a decline in ankle flexibility can increase the risk of falls among older adults. Individuals with HV display a decrease in ankle dorsiflexion during terminal stance compared to controls. Therefore, maintaining adequate toe flexor muscle strength and ankle flexibility in older adults is essential to ensure a safe walking experience. Recognizing the implications of toe flexor muscle strength and ankle flexibility on the aging population is imperative to prevent falls in older adults, which can cause severe injuries and negatively impact their QoL [13]. Furthermore, it is also essential to develop interventions that can enhance toe flexor strength and ankle flexibility in older adults, thus improving their mobility and reducing the risk of falls [15].

The aforementioned observation lends credence to the notion that limited ankle dorsiflexion could potentially play a role in the onset of HV by causing premature and heightened forefoot loading. Moreover, there may be an inclination to overcompensate by externally rotating the foot, which could escalate valgus forces exerted on the hallux [24]. It is thus crucial to consider the potential impact of ankle dorsiflexion restrictions in assessing and managing HV. The study, which involved examining 157 healthy individuals with varying degrees of HV, revealed a noteworthy correlation between the severity of the condition and a proportional decrease in hallux plantarflexion strength in a dose-dependent manner [8].

HV most commonly affects lower limb joints [10]. According to some studies, the extent of the HV angle is directly proportional to the degree of pelvis retroversion [25]. Another study found that in individuals with HV, the stance phase was prolonged compared to the control group while walking speed and step length on regular and irregular surfaces were decreased. However, young and old individuals experience a decrease in walking speed, and young people also experience a speed reduction [13, 26].

Typically, the lower limb joints are intricately linked during walking and move multifacetedly. However, this natural process is hindered by HV, a foot ailment prone to affect the lower extremities. Still, the association between HV and the kinematic parameters of the lower limb joints has not been thoroughly explored. Additionally, there is a shortage of research comparing angular velocity or acceleration between healthy individuals and those affected by HV. As a result, this study aims to investigate whether there are any disparities in acceleration during gait between young and older women with HV and their healthy counterparts.

Materials and Methods

This study used G*Power, software, version 3.1.9.4 to achieve a power level of 0.80 for an effect size of 0.80 and alpha of 0.05. The study comprised 48 women divided into 24 young (healthy and HV) and 24 older (healthy and HV). The participant's age, height, and weight were recorded. The inclusion criteria for the study were the presence of bilateral HV deformity in both young and old groups. Additionally, the severity of the deformity was evaluated using the footprint method to ensure that it was more than 20 degrees and symmetric (less than 5 degrees). No additional malformations were observed in the lower extremities, nor were any significant deformities present in the upper extremities, such as scoliosis. Right limb dominance was also taken into consideration. The healthy group of subjects exhibited no deformities in the lower extremities, and only moderate to severe deformities in the upper limbs were present. These observations prevented numerous subjects from participating in the study process, necessitating a prolonged period to complete the statistical sample.

The current study utilized an inertial measurement unit (IMU)-based motion capture system, specifically the BSN laboratory system located in Guilan, Iran, to gather data on the kinematics of motion [27, 28]. This system consists of various sensors, modules, and traps designed to hold the sensors in place securely. The traps come in three sizes (long, moderate, and short) and are strategically placed to contour the joints and fasten around limbs. Using a wireless connection, the module positions are transmitted to a central processor in a 3-axis coordinate system (x, y, z). This system allows for the measurement and computation of joint kinematic variables, linear and angular velocity/acceleration, and gait cycle. Biomechanical variables were assessed at an ideal speed during forward gait, specifically the stance and swing phases.

Before data collection, all modules were carefully calibrated and defined, then securely fastened around the right thigh, shank, and foot. To ensure accurate measurement, the y-axis of the modules was aligned with the distal head of the limbs, and the modules were strategically placed on the sagittal plane of the thigh and shank and the horizontal plane of the foot. Before executing the

Table 1. The subjects' characteristics, age, weight, and height

Group		Height (cm)		Weight (N)		Age (y)	
		Mean±SD	P	Mean±SD	P	Mean±SD	P
Young	Healthy	166.25±4.95	0.61	633.8±90.2	0.69	24.88±3.76	0.19
	HV	164.88±5.54		617.5±65.6		27±2	
Old	Healthy	160.12±3.31	0.71	678.8±70.7	0.98	54.25±2.76	0.87
	HV	159.25±5.7		677.5±87.3		54.5±3.25	

Iranian Rehabilitation Journal

principal trial, each participant completed two preliminary trials to assess the capturing process. The principal trial consisted of walking forward with five gait cycles while barefoot. We analyzed and displayed angular displacement using the middle steps, specifically the second or third steps. Each participant had four trials: Two for testing the capturing process without saving data and two with data saved. The sampling rate frequency was 333 Hz, with intervals of 3 ms. Gait events, such as heel contact and toe-off, were identified through an algorithm in the IMU software. We differentiated angles around the sagittal, frontal, and vertical axes to calculate angular velocity concerning time intervals. Subsequently, we determined angular acceleration through differentiation from velocity. The data was normalized based on gait cycle percentage using the cubic spline method in the MATLAB software [29].

Data analysis was done using MATLAB software, version 2019. The independent t-test was used to analyze the data statistically.

Results

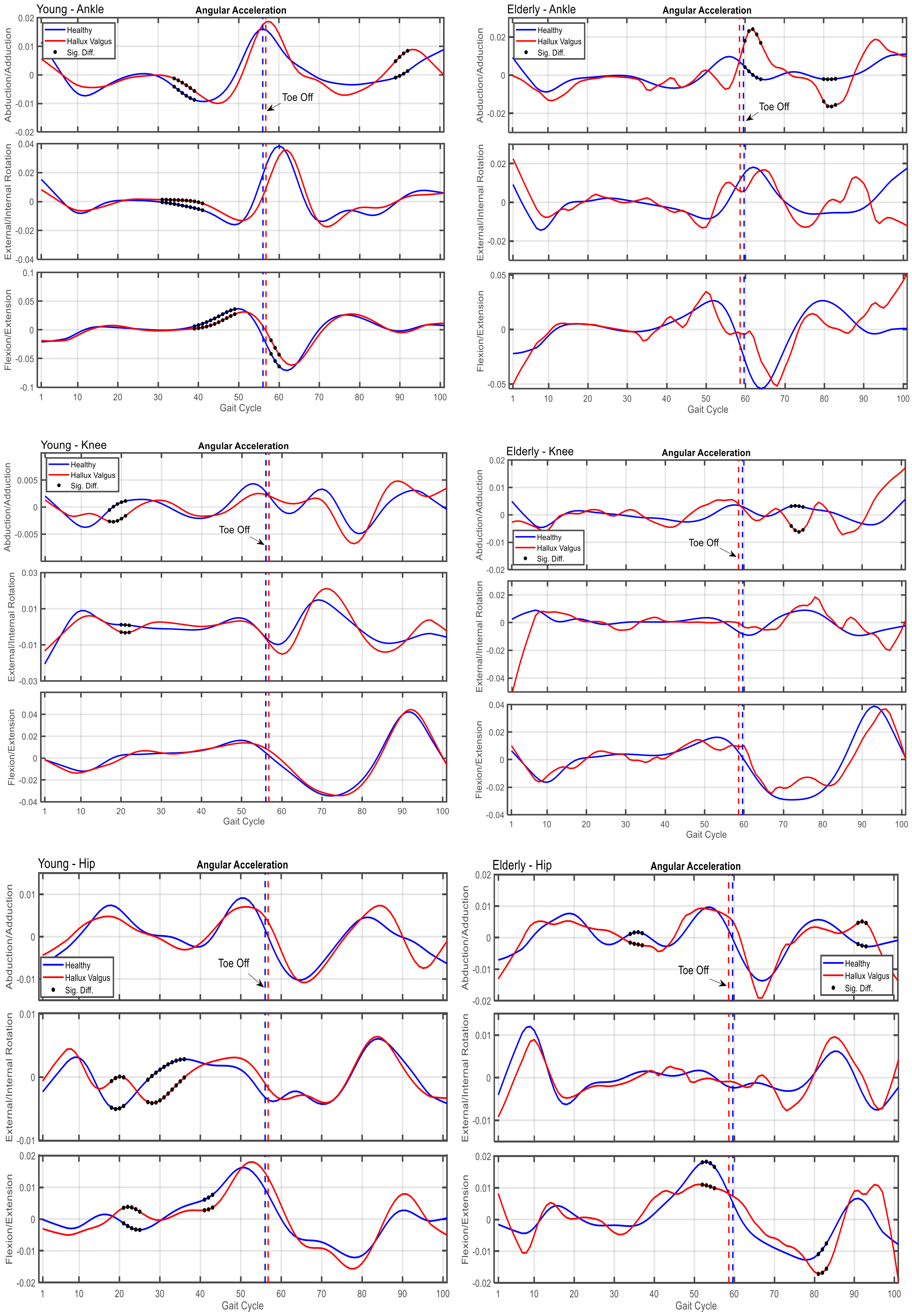
In this investigation, 48 participants were included in two groups: Young (12 healthy individuals and 12 individuals with HV) and elderly (also composed of 12 healthy individuals and 12 individuals with HV). The significance level for this study was set at $P \leq 0.05$, and the demographic findings, along with the participants' stance phase, have been illustrated in Table 1. Our observations found no statistically significant differences in variables such as the subject's age, weight, and stance phase, with the $P > 0.05$.

Furthermore, we have depicted ankle angular acceleration around the frontal, horizontal, and sagittal planes during a gait cycle for both the healthy and HV young groups through Diagrams 1 to 3 (Figure 1). Diagram 1 reveals that abduction/adduction is significantly different during 34%-39% and 89-92% of the gait cycle. Moving on to Diagram 2, it has been observed that external/internal rotation is significantly different during 31%-41% of the gait cycle. Finally, Diagram 3 has highlighted that flexion/extension angular acceleration is significantly different during 39%-49% and 48%-50% of the gait cycle.

Diagrams 4-6 exhibit the angular acceleration of the ankle with respect to the frontal, horizontal, and sagittal planes in both healthy and HV elderly cohorts (Figure 1). It is evident from Diagram 4 that the abduction/adduction angular acceleration is notably distinct during 60%-64% and 80%-83% of the gait cycle. Diagram 5 shows no significant difference concerning internal/external angular acceleration between the two groups. Similarly, Diagram 6 shows no noteworthy difference in flexion/extension angular acceleration between the two groups.

Diagrams 7-9 depict the angular acceleration of the knee in the frontal, horizontal, and sagittal planes during a gait cycle in two cohorts of young individuals, one afflicted with HV and the other healthy (Figure 1). In Diagram 7, it is evident that the angular acceleration of abduction/adduction is significantly dissimilar between the two groups during 17%-21% of the gait cycle. Similarly, Diagram 8 portrays that the external/internal rotation angular acceleration differs significantly between the two groups during 20%-22% of the gait cycle. Conversely, the analysis of Diagram 9 reveals no notable distinctions between the healthy and HV cohorts regarding hip flexion/extension angular acceleration during a gait cycle.

Diagrams 10-12 exhibit the angular acceleration of the knee in the frontal, horizontal, and sagittal planes during a gait cycle in two cohorts of elderly individuals, one of which is healthy. In contrast, the other presents with HV (Figure 1). Diagram 10 demonstrates that the angular acceleration of abduction/adduction varies significantly between 72%-75% of the gait cycle. Conversely, Dia-



Iranian Rehabilitation Journal

Figure 1. Ankle, knee and hip angular acceleration (M/s²) in young (healthy and HV) and old (healthy and HV) women during a gait cycle

gram 11 indicates that the angular acceleration of external/internal rotation does not differ significantly between the two aforementioned elderly groups during the gait cycle. Finally, Diagram 12 illustrates that the angular acceleration of flexion/extension is not significantly different between the healthy and HV elderly groups during the gait cycle.

Diagrams 13-15 depict the angular acceleration of the knee with respect to the frontal, horizontal, and sagittal planes during a gait cycle in two groups of young individuals, one healthy and the other presenting HV (Figure 1). Diagram 13 shows no significant difference in the abduction/adduction angular acceleration between the two groups during the gait cycle. In Diagram 14, it is indicated that there is a significant difference in the internal/external rotation angular acceleration during 18%-21% and 27%-36% of the gait cycle. Finally, Diagram 15 reveals a significant difference in the flexion/extension angular acceleration during 21%-25% and 41%-43% of the gait cycle between two groups of elderly individuals, one healthy and the other presenting HV.

Diagrams 16-18 depict the angular acceleration of the hip joint about frontal, horizontal, and sagittal planes during a gait cycle in two groups of elderly individuals, one consisting of healthy participants and the other of individuals with HV (Figure 1). Analysis of Diagram 16 reveals significant discrepancies in abduction/adduction angular acceleration between 34%-37% and 91%-93% of the gait cycle. Conversely, as evidenced in Diagram 17, no marked differences are discernible between the healthy and HV elderly groups concerning hip external/internal rotation angular acceleration during a gait cycle. Lastly, Diagram 18 highlights that flexion/extension angular acceleration significantly varies at 52%-55% and 81%-83% of the gait cycle.

Discussion

The angular acceleration of the ankle joint in the frontal plane exhibits significant differences between two groups of young individuals: One healthy and the other afflicted with HV, ranging between 34% and 39% of the gait cycle. The HV group appears to spend more time in the neutral position, thereby delaying the transition to the inversion position compared to the healthy group. This delay leads to a decrease in acceleration during the stance phase. However, during the swing phase, the angular acceleration increases smoothly, and the HV group exhibits a sudden enhancement in inversion angular acceleration just before heel contact.

Both groups, the HV group, and the healthy elderly group, undergo significant changes in angular acceleration during both the stance and swing phases. Immediately after toe-off, the healthy group experiences an angular acceleration of approximately zero, and the inversion angle decreases with high acceleration. This finding is likely a compensatory response to the substantial increase in inversion angle at the end of the stance phase (toe-off). According to the findings of this study, elderly individuals with HV exhibit a greater tendency to transfer body weight to the lateral edge of the foot. Specifically, during 31% to 41% of the gait cycle in the horizontal plane, there is a notable discrepancy between healthy young individuals and those with HV. It appears that during the terminal stance phase, when the HV group experiences a near-zero acceleration in the toe-in position, the healthy group displays an increase in toe-out angular acceleration followed by an immediate decrease, resulting in both groups exhibiting the same angular acceleration at the toe-off moment. Although the angular acceleration exhibits successive changes in HV relative to the healthy group, no significant difference is observable between the two groups, perhaps due to the comparable changes caused by aging in the healthy group and the probable effects of HV in the other.

Notably, there are significant differences in ankle dorsiflexion/plantar flexion between the two young groups, particularly at 39% to 49% of the gait cycle. During the terminal stance phase, when the foot position in the healthy group exhibits maximum plantar flexion, the angular acceleration of plantar flexion increases gradually. It appears that plantar flexion, associated with weight bearing on the forefoot, is executed smoothly and with greater caution, perhaps intentionally, to reduce pressure on the first metatarsophalangeal joint. During toe-off in the elderly group, no significant differences were observed between the healthy and HV groups. It seems that in the healthy group, age-related changes are comparable to probable changes caused by HV and do not impact angular acceleration in this group. As for HV in older people, potential deficiencies are compensated for through successive and short amplitude changes (i.e. noisy behavior) of angular acceleration or aging compensatory movements that have been shifted to proximal joints.

The knee angular acceleration of the young cohort during abduction/adduction exhibits significant differences in 17%-21% of the gait cycle. Following heel contact, when the knee intends to assume an adduction position, the angular acceleration of the HV group increases with a delay. Presumably, from the commencement of the gait cycle, the knee had undergone less abduction compared to the healthy group, requiring less time to achieve an adduction position simultaneously. The enhanced adduction of the HV group may be attributed to a propensity to shift body weight onto the lateral edge of the foot when the foot is flat.

At the end of the initial swing phase (72%-75% of the gait cycle), the HV in the older group shows a negative enhancement of angular acceleration to reduce the knee adduction angle (minimal adduction angle throughout the gait cycle). At the temporal threshold of 72%-75% of the gait cycle, there is evidence of a positive trend in angular acceleration toward attaining maximum adduction. Notably, no significant differences were observed in the angular acceleration of internal/external rotation between healthy individuals and those with HV in the elderly cohort. Although the older group exhibited noisy behavior in successive and short amplitude changes of angular acceleration, there were no significant differences between the two groups. Additionally, there were no significant differences in knee flexion/extension angular acceleration between the healthy and HV groups, and the trends were similar. These results suggest that HV has a lesser impact on the knee joint than other joints, particularly in the sagittal plane. Although there were variations in the amplitude of knee flexion/extension angular acceleration, no significant differences were observed between the two groups of elderly participants: One healthy and the other with HV.

Similarly, there were no significant differences in hip abduction/adduction angular acceleration between the young healthy group and the young HV group. However, it is noteworthy that during the 30%-40% of the gait cycle, where the angular acceleration of the abduction angle reduction increases, there were no significant differences in abduction/adduction angular acceleration in the healthy group, while in the HV group, adduction showed a slight increase accompanied by negative and additive angular acceleration (a bit less than zero). The preference of the HV group for a less adducted hip suggests the need for expansion of the support area and transfer of body weight to the lateral edge of the foot during ambulation.

In the younger cohort, the angular acceleration of internal/external hip rotation exhibited significant differences between the two groups, occurring at 27%-36% of the gait cycle but was comparable during the swing phase. It appears that during midstance (specifically at the 20% point), the HV group experiences an angular acceleration close to zero. In contrast, in the gait cycle, the healthy group approached a negative peak (valley). This significant difference in angular acceleration is attributed to a delay caused by an additive wave at 20% of the gait cycle.

Table 2 presents the range of angular acceleration in joints with significant difference points during a gait cycle between the healthy and HV young groups in all planes.

Table 3 presents the range of angular acceleration in joints with significant difference points during a gait cycle between the healthy and HV elderly groups in all planes.

The older group displayed successive changes in angular acceleration, characterized by noisy behavior. However, no significant difference was observed. Changes in angular acceleration resulting from aging are likely comparable to those resulting from HV deformity.

Hip flexion/extension angular acceleration demonstrated significant differences between the two young groups, specifically during the 21%-25% of the gait cycle. Additionally, during foot flat, the healthy group exhibited negative angular acceleration, whereas the HV group displayed a decrease in positive angular acceleration.

Individuals with HV may compensate at heel contact by promoting extension angular acceleration in the hip rather than flexion. Analysis of angular acceleration at

Table 2. Points of significant differences during a gait cycle in the young group

Movement Joint	Abduction/Adduction		External/Internal Rotation		Flexion/Extension	
	Range	Total Points (%)*	Range	Total Points (%)	Range	Total Points (%)
Ankle	34-39 89-92	9	31-41	11	39-49 48-50	14
Knee	17-21	8	20-22	3	None	0
Hip	None	0	18-21 27-36	14	21-25 41-43	8

*Sum of the significantly different points throughout a gait cycle.

Iranian Rehabilitation Journal

Table 3. Points of significant differences during a gait cycle in the older group

Movement Joint	Abduction/Adduction		External/Internal Rotation		Flexion/Extension	
	Range	Total Points (%)*	Range	Total Points (%)	Range	Total Points (%)
Ankle	60-64 80-83	9	None	0	None	0
Knee	72-75	4	None	0	None	0
Hip	34-37 91-93	7	None	0	52- 55 81- 83	7

*Sum of the significantly different points throughout a gait cycle.

the end of the stance phase, just before toe-off, reveals that the HV group experiences a significantly smaller positive peak (0.01) than the healthy group (0.02). With respect to hip strategy for balance retrieval in this age range [15, 30], it appears that the HV group may need to extend the hip further during toe-off, in contrast to the healthy group. This may result in a greater enhancement of angular acceleration (decelerating acceleration) at the end of the swing phase, simultaneously with the single support of the opposite leg, to facilitate early heel contact and avoid complete weight bearing on the forefoot of the opposite leg.

These findings, alongside similar research, provide a set of characteristics that can be used to trace the effectiveness of corrective exercises or balance-based programs or even as a diagnostic tool to ensure the practical impact of this deformity in the HV population.

All diagram summarizations are observable in Tables 2 and 3. They show the percentage of different points of angular acceleration that exist in the specific joint plane between the healthy and HV groups during a gait cycle.

Conclusion

The comparison of angular acceleration between healthy individuals and those with HV deformity in both the young and older populations has revealed that the ankle joint in the young group is affected by the deformity in all planes. In contrast, in the older group, only the plane of inversion/eversion movement is influenced. It has been observed that the knee joint in both the young and healthy groups is less affected by HV deformity compared to other joints. In the young group, the deformity affects both internal/external rotation and flexion/extension angular acceleration of the hip, whereas, in the older group, the deformity affects the angular acceleration of hip abduction/adduction and flexion/extension movements. All findings support the idea that individuals with HV, especially in the young group, attempt to compensate for the negative impact of the condition by altering the angular acceleration of the ankle, knee, and hip joints.

Ethical Considerations

Compliance with ethical guidelines

The Ethics Committee of Sport Sciences Research Institute approved this research (Code: IR.SSRI.REC.1401.1505).

Funding

The paper was extracted from the PhD dissertation of Samaneh Sardary, approved by the Department of Sports Biomechanics, Faculty of Physical Education and Sports Science, Tehran Central Branch, Islamic Azad university, Tehran, Iran.

Authors' contributions

All authors equally contributed to preparing this article.

Conflict of interest

The authors declared no conflict of interest.

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