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Compensatory sagittal plane ankle gait mechanics: Are they present in patients with a weak or stiff hip?

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ABSTRACT

Introduction: Simulations suggest that subjects with reduced hip range of motion (ROM) and/or weakness can achieve more normal walking mechanics through compensations at the ankle. The aims of this study were to assess whether subjects with reduced hip ROM (Stiff hip) or hip flexor weakness (Weak hip) exhibit ankle compensations during walking and investigate redistribution of power in the lower extremity joints.

Methods: Retrospective gait data were reviewed (IRB-approved hip registry). Preoperative kinematic/kinetic walking data were collected in patients with: adolescent hip dysplasia (AHD), femoral acetabular impingement (FAI), and Legg-Calvé Perthes disease (Perthes). AHD patients with significantly weak hip flexors on their affected side were included (Weak hip group). The Gait Profile Score (GPS) was calculated on the affected side of the FAI and Perthes groups to identify patients who had a Stiff hip. Patients who had undergone a hip arthrodesis (Fusion) were also included (Stiff hip group). Ankle kinematics/kinetics were compared to healthy participants (Control). The total positive work of sagittal plane hip, knee and ankle power were compared along with the distribution of power.

Results: Patients in the Weak/Stiff hip groups did not walk with greater ankle plantarflexion, peak push-off power or positive ankle work on their affected sides compared to Control. Ankle work contribution (percentage of total positive work) on the affected or unaffected sides was greater in the Perthes and Hip Fusion patients compared to Control. Significant gait abnormalities on the unaffected side were observed.

Conclusions: Patients with a weak or stiff hip did exhibit altered ankle mechanics during walking. Greater percent ankle work contribution appeared to correspond with hip stiffness. In patients with hip pathology the redistribution of power among the lower extremity joints can highlight the importance of preserving ankle function.

1. Introduction

Research using forward dynamics simulations of walking have suggested that older adult subjects with musculoskeletal deficits such as increased hip joint stiffness or diminished hip flexor strength, rely on compensatory mechanisms of the ankle plantar flexors [1]. An experimental reduction in the burst of mechanical ankle power in late stance revealed greater net metabolic power expenditure to maintain walking speed [2]. This increased metabolic demand and the resultant redistribution of work across the lower extremity joints, results in poorer energy efficiency/walking economy. This is an important realization to consider in subjects with musculoskeletal deficits.

The ankle plantar flexor muscles have been shown to be the primary generators of positive power during human walking [3–6] contributing to leg swing and the acceleration of the center of mass [7]. Increasing ankle power output in young adults during treadmill walking showed a reduction in the mechanical power demands at the hip [8].

The compensatory mechanism of the redistribution of mechanical power between the hip and ankle has been investigated in numerous comparative studies of younger and older healthy adults but not exclusively in patients with hip pathology [9–14]. Limited research is available investigating this phenomenon in patients with a stiff or weak hip as a result of various hip pathologies and/or surgical procedures. Gordon et al, investigated six adolescent subjects with a severely stiff hip. These subjects did not walk with greater peak ankle power generation in late stance (compared to healthy controls) and had a significantly reduced Gait Deviation Index [15,16]. In patients with untreated hip dysplasia, gait analysis has shown reduced walking velocity and deficits in the hip flexors which result in altered hip joint moments throughout stance phase [17–20]. Karol et al studied 13 patients who

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had undergone a hip arthrodesis (2–13 years post surgery) and showed that the ankle plantarflexion strength on the fused side was stronger in six of the patients [21]. A greater understanding of the redistribution of mechanical power proximally to distally in patients with hip pathology would provide clinicians further insight on their patients' walking mechanics/efficiency. Additionally, rehabilitation paradigms in patients with hip deformities can be advanced to focus on preserving optimal walking mechanics of the distal joints.

The purpose of this study was to investigate whether unilaterally affected subjects with reduced hip ROM (*Stiff* hip) and/or hip flexor weakness (*Weak* hip) exhibit sagittal plane ankle compensations in their gait mechanics and analyze the redistribution of power among the lower extremity joints.

2. Methods

A retrospective analysis of gait data collected between 2005–2017 was performed as part of a larger institutional review board approved hip registry. Adolescent patients with various hip pathologies who were scheduled for hip preservation surgery were prospectively enrolled. Patients with an underlying syndromic or neurologic condition such as Charcot-Marie-Tooth, Down syndrome or Cerebral Palsy were excluded from this analysis. Pre-operative patients with the following unilateral diagnoses were included: acetabular hip dysplasia (AHD), femoral acetabular impingement (FAI) and Legg-Calvé Perthes disease (Perthes). Patients who underwent a unilateral hip arthrodesis (Hip Fusion) as an adolescent (avg. age 14 ± 2 years) and returned for long-term follow-up (avg. follow-up 21 ± 11 years post-surgery) were also included.

2.1. Kinematic/kinetic/strength data collection and processing

Kinematic and kinetic data during self-selected speed walking were collected using a 12 camera VICON motion capture system (VICON Motion Systems Ltd, Denver, CO, USA) sampled at 120 Hz along with five AMTI force platforms (AMTI, Watertown, MA, USA) sampled at 3000 Hz. Patients were instrumented with a modified Plug-In-Gait (PIG) marker set [22]. A Woltring filtering routine was applied with a predicted mean square error of 10 mm^2 [23]. The PIG Biomechanical Modeler (version 2.0.1) in the VICON Nexus software was used to calculate joint angles, moments and powers. Walking speed and step length were calculated in the VICON software [24]. Representative walking trials for the affected and unaffected sides were selected, with a single stride identified for each side which included a clean force platform strike. Strides were normalized to the gait cycle (0–100%). Isokinetic hip flexor strength was measured in the supine position at 60 degrees per second using a Biodex System 3 (Biodex Medical Systems, NY, USA) using methods previously published [19]. A control cohort (Control) of 20 healthy adults (9 females, avg. age 22 ± 2 yrs.) with no orthopaedic or neurologic conditions were included in this analysis.

2.2. Weak hip cohort

The *Weak* hip cohort was identified from pre-operative patients with unilateral AHD who had peak isokinetic hip flexor strength (on the affected hip) of less than 50% of normative healthy control values (n = 100 subjects: Males: 1.58 N-m/kg, Females: 1.07 N-m/kg) from the lab database. Of the 98 total AHD patients queried, 83 patients were excluded for not meeting the strength criterion, two patients were excluded for not having trunk kinematic data and seven patients were excluded for having bilateral hip dysplasia. There were six AHD patients (Females n = 3) who met the criterion and were included in this analysis as the *Weak* hip cohort (Table 1).

2.3. Stiff hip cohort

The *Stiff* hip cohort comprised of pre-operative patients with unilateral FAI, Perthes and post-operative unilateral THA long term follow-up patients. The Gait Profile Score (GPS) which allows for a single measure of the gait differences (compared to a healthy control group) of a subject's overall walking ability and the Gait Variable Scores (GVS), the differences in specific GPS kinematic variables (map) were calculated [25]. The GVSmap of the sagittal plane hip kinematics was calculated in the FAI, Perthes, and Hip Fusion groups. Using the methods proposed by Schwartz et. al [26], the GVS score was converted to the Gait Deviation Index (GDI) scale [16], with GVSmap scores greater than 90 considered normal kinematics. Patients with a sagittal hip motion GVSmap less than 80 were included in this analysis. Of the 77 FAI and 54 Perthes pre-operative patients queried, 9 FAI (6 Females) and 8 Perthes (1 Female) patients met the criterion (Table 1). As expected, all of the 9 long term follow-up Hip Fusion (6 Females) patients met the criterion (Table 1).

2.4. Kinematic/kinetic data analysis and statistics

Peak ankle plantarflexion along with peak positive ankle power were calculated. Sagittal plane hip, knee and ankle power were normalized to height, weight and gravity for the purposes of minimizing individual differences due to subjects' anthropometric measurements and reporting as a dimensionless quantity. [27]. Walking speed was also calculated and normalized to height and gravity [27]. The area under the positive portion of the power curve across the gait cycle was calculated at the hip, knee, ankle and was reported as a dimensionless work variable (work). The distribution of positive work across the joints was reported as a percentage of the total positive work of all three joints. A Kruskal Wallis test ($\alpha = 0.05$) was used to compare the kinematic and kinetic variables of the affected and unaffected sides of each hip group to Control.

3. Results

All patient groups walked significantly slower than Control ($p < 0.05$) and the affected side GPS was significantly higher in the *Stiff* hip group ($p < 0.05$) indicating greater overall walking impairment (Table 1). The GPS on the unaffected side was significantly higher in both the *Weak* and *Stiff* hip groups compared to Control ($p < 0.05$). In the Perthes patients step lengths were significantly shorter on the affected side (0.36 ± 0.06) and longer on the unaffected side (0.56 ± 0.10) when compared to Control (0.41 ± 0.03). The Hip Fusion patients had reduced step lengths bilaterally (affected side = 0.36 ± 0.03, unaffected side = 0.30 ± 0.03, $p < 0.05$).

In the *Weak* hip group, the AHD patients on their affected side, did not have a statistically greater peak plantarflexion compared to Control (AHD 31.0 ± 6.0° vs. Control 23.5 ± 8.7°, p = 0.05) or peak power (AHD 0.09 ± 0.03 vs. Control 0.12 ± 0.03, p = 0.08) (Table 2). Similar results were found on the unaffected side (Table 3). In the *Stiff* hip group the Perthes patients had reduced ipsilateral ankle plantarflexion compared to Control (Perthes 13.8 ± 7.3° vs. Control 23.5 ± 8.7°, p = 0.02) which was not seen in the FAI (FAI 24.0 ± 8.1° vs. Control 23.5 ± 8.7°, p = 0.92) and Hip Fusion (Hip Fusion 23.3 ± 12.0° vs. Control 23.5 ± 8.7°, p = 0.67) groups (Table 2). There was no statistical difference in ankle plantarflexion on the contralateral side for patients in the *Stiff* hip group when compared to Control ($p > 0.05$) (Table 3). Peak ankle power was significantly reduced on the affected side in the *Stiff* hip group ($p < 0.05$) and the unaffected side in the Perthes patients ($p < 0.01$) (Tables 2,3). There was no significant reduction in ipsilateral or contralateral ankle power in the *Weak* hip group when compared to Control.

Hip work was not statistically different on either side in the *Weak* hip group ($p > 0.05$) but was statistically lesser on the affected sides of

Table 1
Demographics of *Stiff* hip, *Weak* hip groups and Control; *Weak* hip group (n = 6 patients): Acetabular Hip Dysplasia (AHD) patients with reduced isokinetic hip flexor strength (N*m/kg); *Stiff* hip (n = 26 patients): Femoral Acetabular Impingement (FAI), Legg-Calvé Perthes (Perthes), Hip Arthrodesis (Hip Fusion) patients identified using the sagittal plane kinematic hip Gait Variable Score (GVSmap) [25,26] less than < 80 (scores converted to Gait Deviation Index scale out of 100 [16]) on their affected side; Speed normalized to height and gravity; Step Length normalized to height; GPS – Gait Profile Score of walking; (Mean ± SD) *p < 0.05, significantly different from Control.

Variable	*Weak* hip		*Stiff hip*		Control
	AHD	FAI	Perthes	Hip Fusion	
Patient Count	6	9	8	9	20
Gender (females)	3	6	1	6	9
Height (m)	1.6 ± 0.1	1.7 ± 0.1	1.7 ± 0.1	1.7 ± 0.1	1.7 ± 0.1
Weight (kg)	55 ± 6	70 ± 22	73 ± 19	106 ± 24	73 ± 13
Age (years)	15 ± 3	16 ± 2	15 ± 2	34 ± 10	22 ± 2
Speed	0.30 ± 0.03*	0.29 ± 0.04*	0.27 ± 0.06*	0.23 ± 0.05*	0.33 ± 0.03
Hip Flexor Strength (N*m/kg)	0.5 ± 0.2	–	–	–	1.3 ± 0.4
Affected Side GVSmap Hip	97 ± 15	71 ± 5	56 ± 5	52 ± 6	99
Affected Step Length	0.39 ± 0.02	0.39 ± 0.04	0.36 ± 0.06*	0.36 ± 0.03*	0.41 ± 0.03
Unaffected Step Length	0.39 ± 0.03	0.51 ± 0.15	0.56 ± 0.10*	0.30 ± 0.03*	
Affected GPS (°)	5.8 ± 1.8	6.5 ± 1.4*	10.5 ± 2.1*	10.5 ± 2.0*	4.5 ± 1.1
Unaffected GPS (°)	6.2 ± 1.5*	6.0 ± 1.7*	9.2 ± 2.7*	9.5 ± 2.3*	

the patients in the *Stiff* hip group compared to Control. As expected the fused side of the Hip Fusion patients had the lowest hip work (0.09 ± 0.04). The FAI patients had reduced hip work bilaterally when compared to Control (FAI affected side 0.45 ± 0.17 p = 0.008, unaffected side 0.43 ± 0.12 p = 0.002 vs. Control 0.68 ± 0.18).

Knee work was significantly reduced only on the affected side in the *Weak* hip group (AHD affected side 0.16 ± 0.09 vs. Control 0.27 ± 0.10, p = 0.02). In the *Stiff* hip group the FAI patients had a reduction in knee work on the affected and unaffected sides (p < 0.05), the Perthes patients had no statistically significant difference on the affected and unaffected sides (p > 0.05) and the Hip Fusion patients had significantly lesser knee work on the affected side only compared to Control (Hip Fusion affected side 0.08 ± 0.04 vs. Control 0.27 ± 0.10, p < 0.001) (Tables 2,3).

There was no statistically significant difference in ankle work in the *Weak* hip group compared to Control (p > 0.05). In the *Stiff* hip group the FAI patients had no significant difference on the affected and unaffected sides, the Perthes patients had a significant reduction on the affected side only (Perthes affected side 0.66 ± 0.18 vs. Control 0.88 ± 0.26, p = 0.04) (Table 2) and the Hip fusion patients had no significant difference compared to Control (p > 0.05) (Tables 2,3).

The total positive work on the affected and unaffected sides was not significantly different in the *Weak* hip group (Tables 2,3) compared to Control. In the *Stiff* hip group, the FAI patients had significantly lesser total positive work bilaterally (p < 0.05), and the Perthes and Hip Fusion patients had a significant reduction on the affected sides only (Perthes affected side 1.12 ± 0.45 vs. Control 1.83 ± 0.41, p = 0.002, Hip Fusion affected side 0.94 ± 0.39 vs. Control 1.83 ± 0.41, p < 0.001) (Table 2).

The distribution of positive work at each joint for the affected and unaffected sides separately, were reported as a percentage of total work across all joints (Figs. 1,2). The AHD patients (*Weak* hip group) demonstrated no significant difference in the positive work percent contribution across all joints, on the affected and unaffected sides, when compared to Control (p > 0.05). In the *Stiff* hip group on the affected side, the Perthes (24 ± 14%, p = 0.02) and Hip Fusion (10 ± 4%, p < 0.001) patients had significantly lesser hip work percent contribution compared to Control (37 ± 6%) along with significantly greater ankle work percent contribution (Perthes 64 ± 19% p = 0.04, Hip Fusion 81 ± 9% p < 0.001 vs. Control 48 ± 5%) (Fig. 1). The Hip Fusion patients on their affected side had lesser knee positive work percent contribution (Hip Fusion affected side 9 ± 7% vs. Control 15 ± 5%, p = 0.02).

In the *Stiff* hip group on the unaffected side, the FAI patients had significantly lesser hip work percent contribution (FAI 31 ± 5% vs Control 37 ± 6%, p = 0.01) and a greater ankle work percent contribution (FAI 57 ± 8% vs Control 48 ± 5%, p < 0.01) compared to Control (Fig. 2). The Hip Fusion patients on the unaffected side had a significantly greater hip work percent contribution (Hip Fusion 43 ± 7% vs Control 37 ± 6%, p = 0.03) and a lesser ankle work percent contribution (Hip Fusion 41 ± 6% vs Control 48 ± 5%, p < 0.01) compared to Control. There was no statistically significant difference on the unaffected side of the Perthes patients compared to Control.

4. Discussion

The current study has demonstrated that patients with a stiff or weak hip did not exhibit greater ankle plantarflexion or push-off power. Lesser peak ankle power was observed in the *Stiff* hip group on their

Table 2
Affected side gait outputs. Ankle kinematics/kinetics for the *Weak* hip and *Stiff* hip groups compared to Controls; Power normalized to height, weight and gravity [27]. Positive work (area under the positive curve) of the sagittal hip, knee and ankle power; Diagnoses included: Acetabular Dysplasia (AHD), Femoral Acetabular Impingement (FAI), Legg-Calvé Perthes (Perthes), Hip Arthrodesis (Hip Fusion); (Mean ± SD) *p < 0.05, significantly different from Control;

Variable	*Weak* hip		*Stiff hip*		Control
	AHD	FAI	Perthes	Hip Fusion	
Ankle Plantarflexion (º)	31.0 ± 6.0	24.0 ± 8.1	13.8 ± 7.3*	23.3 ± 12.0	23.5 ± 8.7
Ankle Peak Power	0.09 ± 0.03	0.09 ± 0.02*	0.09 ± 0.03*	0.09 ± 0.05*	0.12 ± 0.03
Hip Work	0.54 ± 0.24	0.45 ± 0.17*	0.31 ± 0.30*	0.09 ± 0.04*	0.68 ± 0.18
Knee Work	0.16 ± 0.09*	0.17 ± 0.08*	0.14 ± 0.11	0.08 ± 0.04*	0.27 ± 0.10
Ankle Work	0.82 ± 0.17	0.70 ± 0.18	0.66 ± 0.18*	0.78 ± 0.39	0.88 ± 0.26
Total Positive Work	1.52 ± 0.33	1.32 ± 0.31*	1.12 ± 0.45*	0.94 ± 0.39*	1.83 ± 0.41

Table 3
Unaffected side gait outputs. Ankle kinematics/kinetics for the *Weak* hip and *Stiff* hip groups compared to Controls; Power normalized to height, weight and gravity [27]. Positive work (area under the positive curve) of the sagittal hip, knee and ankle power; Diagnoses included: Acetabular Dysplasia (AHD), Femoral Acetabular Impingement (FAI), Legg-Calvé Perthes (Perthes), Hip Arthrodesis (Hip Fusion); (Mean ± SD) *p < 0.05, significantly different from Control;

Variable	*Weak* hip		*Stiff hip*		
	AHD	FAI	Perthes	Hip Fusion	Control
Ankle Plantarflexion (°)	25.8 ± 5.9	22.4 ± 8.5	21.6 ± 11.9	16.5 ± 8.3	23.5 ± 8.7
Ankle Peak Power	0.10 ± 0.03	0.10 ± 0.03	0.08 ± 0.03*	0.10 ± 0.04	0.12 ± 0.03
Hip Work	0.52 ± 0.16	0.43 ± 0.12*	0.56 ± 0.22	0.69 ± 0.25	0.68 ± 0.18
Knee Work	0.24 ± 0.13	0.17 ± 0.07*	0.22 ± 0.16	0.27 ± 0.14	0.27 ± 0.10
Ankle Work	0.82 ± 0.29	0.79 ± 0.28	0.69 ± 0.25	0.67 ± 0.26	0.88 ± 0.26
Total Positive Work	1.58 ± 0.36	1.40 ± 0.39*	1.46 ± 0.42	1.63 ± 0.58	1.83 ± 0.41

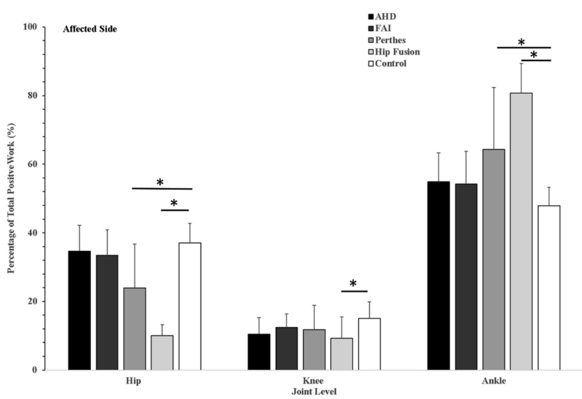

Fig. 1. Affected side distribution of positive work at the hip, knee and ankle, reported as a percentage of total positive work for the *Stiff* and *Weak* hip groups; Diagnoses included: Acetabular Dysplasia (AHD), Femoral Acetabular Impingement (FAI), Legg-Calvé Perthes (Perthes), Hip Arthrodesis (Hip Fusion); Control group included for comparison; Perthes and Hip Fusion patients had a significantly reduced hip positive work percent contribution and a significantly increased ankle positive work percent contribution; *p < 0.05, significantly different from Control.

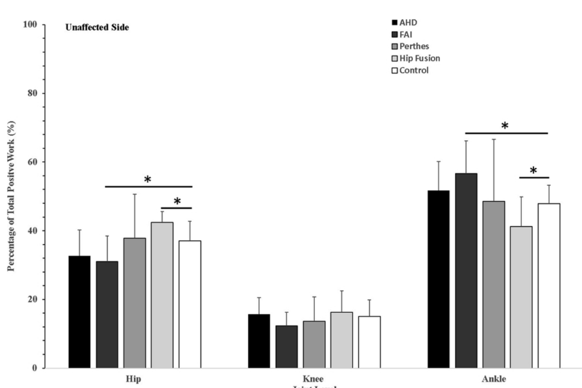

Fig. 2. Unaffected side distribution of positive work at the hip, knee and ankle, reported as a percentage of total positive work for the *Stiff* and *Weak* hip groups; Diagnoses included: Acetabular Dysplasia (AHD), Femoral Acetabular Impingement (FAI), Legg-Calvé Perthes (Perthes), Hip Arthrodesis (Hip Fusion); Control group included for comparison; FAI patients had a significantly reduced hip positive work percent contribution and a significantly increased ankle work percent contribution. Opposite finding observed in the Hip Fusion patients. *p < 0.05, significantly different from Control.

affected side. Ankle work on the affected side in both the *Stiff* and *Weak* hip groups was not significantly greater compared to Control. The percent distribution of work across the lower extremity joints on the affected side, showed that the ankle contribution in the Perthes and Hip Fusion patients was significantly greater than Control (Fig. 1).

The hip registry dataset was queried to determine whether patients with various hip deformities would exhibit compensatory ankle mechanics. Goldberg et. al, suggested this compensation by simulating scenarios in which subjects walked with reduced hip ROM or weakness, resulting in greater ankle plantar flexor push off power [1]. In the present study patients with marked weakness in hip flexor isokinetic strength as well as a separate group of patients with significantly reduced sagittal plane hip ROM during self-selected speed walking were assessed. Across patients with various hip deformities, ankle plantarflexion and/or push-off power was not greater on the affected side (Table 2), but it is critical to note that these patients were not achieving normal walking mechanics (Table 1). In the *Stiff* hip group, the GPS was significantly increased and in both the *Stiff* and *Weak* hip groups, walking speed was significantly slower than Control (Table 1). These findings are similar to the case series reported by Gordon et. al [15] as the GDI was significantly reduced on the affected and unaffected sides. The reduced sagittal hip ROM affected the step lengths in the Perthes and Hip Fusion patients as they took shorter steps bilaterally.

The effect of walking speed on gait mechanics has been extensively documented to show that faster movement demands more positive mechanical work [11,28]. Browne et al reported a decrease in total positive joint work across a range of walking speeds (0.9–1.3 meters/second) in young adults [11]. In the current study while the total positive work was reduced on the affected and unaffected sides, statistical significance was only met on the affected sides of the FAI, Perthes and Hip Fusion patients (Table 2), most likely due to small sample size within each diagnosis. Interestingly though, researchers have shown that the proportion of work contributed by each lower extremity joint does not change significantly across various walking speeds in young adults [11,28].

In the current study the distribution of positive work at the lower extremity joints on the affected and unaffected sides are different from Controls. Furthermore, it appears that these changes especially on the affected side, are based on the severity of the hip deformity (Fig. 1). The Perthes patients were assessed prior to undergoing hip preservation surgery and the work percent contribution was highest in the ankle rather than the hip in comparison to Controls. These Perthes patients had significantly reduced sagittal hip ROM (GVSmap Hip:56 ± 5) on their affected side (Table 1). While the AHD and FAI patients demonstrated a similar trend, it did not meet significance. The FAI patients included in this analysis did not exhibit equivalent levels of stiffness (GVSmap Hip:71 ± 5) in comparison to the Perthes cohort. Though the AHD patients had weak hip flexors and their hip work percent contribution was reduced, it did not meet significance (Table 2, Fig. 1).

During self-selected speed walking hip patients did not demonstrate any biomechanical deficiency at the ankle (no difference in peak ankle plantarflexion) however, passive ankle motion was not part of our clinical assessment. Understanding a patient's ROM and strength at the ankle may be important to the rehabilitation process. It is important to note and should be expected, that the Hip Fusion patients' ankle contribution on the affected was 82% of the total positive work across all the joints, which demonstrates the importance of preserving ankle motion/power as a means of maintaining walking function.

In the patient with hemiplegic CP, clinical gait analysis has shown the existence of secondary gait compensatory mechanisms that are of the result of primary abnormalities [29]. Stebbins et. al reported on twelve children with CP who presented with a foot deformity on their hemiplegic side. Gait analysis showed that these children walked with reduced hip extension in stance phase on their unaffected side. In the present study, significant gait abnormalities on the unaffected side in all patient groups were observed. The unaffected side GPS was significantly higher than the Control average and the difference across the various diagnoses ranged from 1.5° to 5° (Table 1). On the unaffected side of the *Stiff* hip group, the FAI patients had significantly reduced positive hip work percent contribution and a resultant greater (compared to Control) ankle contribution. The Hip Fusion patients on their unfused side demonstrated significantly greater hip work percent contribution and reduced ankle contribution. The gait abnormalities on the unaffected side of the patients in the *Stiff* hip group may be an effort to maintain gait symmetry with the reduced hip range of motion on the affected side.

In the present study there are several limitations. There were a small number of patients who met the criterion to be included in both the *Weak* and *Stiff* hip groups. There was not sufficient documentation on the duration of hip symptoms and passive ankle ROM or isokinetic ankle strength was not assessed. The Perthes patients were enrolled following treatment of their hip disease and due to the residual deformity presented with hip pain. The severity of residual femoral head deformity would play a significant role in understanding their walking mechanics. The Hip Fusion patients demonstrated small amounts of positive hip work, despite no true hip motion. This is most likely due to skin motion artifact. Finally, walking speed was not matched across groups and research has shown that power generation in the lower extremity joints is affected by speed.

Further work is needed to analyze the redistribution of positive work across the joints in the AHD, FAI and Perthes patients following hip preservation surgery. Clinicians treating patients with various hip deformities should be aware of a patient's ankle function as preservation of the ankle mechanics may play a role in maintaining and achieving normal gait mechanics.

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Declaration of Competing Interest

The authors have no relevant conflicts of interests to disclose.

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References

[1] E.J. Goldberg, R.R. Neptune, Compensatory strategies during normal walking in response to muscle weakness and increased hip joint stiffness, Gait Posture 25 (2007) 360–367.
[2] T.P. Huang, K.A. Shorter, P.G. Adamczyk, A.D. Kuo, Mechanical and energetic consequences of reduced ankle plantar-flexion in human walking, J. Exp. Biol. 218 (2015) 3541–3550.
[3] H. Elftman, Forces and energy changes in the leg during walking, Am. J. Physiol. 125 (1939) 339–356.
[4] A. Cappozzo, F. Figura, M. Marchetti, A. Pedotti, The interplay of muscular and external forces in human ambulation, J. Biomech. 9 (1976) 35–43.
[5] A.L. Hof, B.A. Geelen, J. Van den Berg, Calf muscle moment, work and efficiency in level walking; role of series elasticity, J. Biomech. 16 (1983) 523–537.
[6] D.A. Winter, Energy generation and absorption at the ankle and knee during fast, natural, and slow cadences, Clin. Orthop. (1983) 147–154.
[7] K.E. Zelik, P.G. Adamczyk, A unified perspective on ankle push-off in human walking, J. Exp. Biol. 219 (2016) 3676–3683.
[8] S.N. Fickey, M.G. Browne, J.R. Franz, Biomechanical effects of augmented ankle power output during human walking, J. Exp. Biol. 221 (2018).
[9] P. DeVita, J. Helseth, T. Hortobagyi, Muscles do more positive than negative work in human locomotion, J. Exp. Biol. 210 (2007) 3361–3373.
[10] J.R. Franz, R. Kram, Advanced age and the mechanics of uphill walking: a joint-level, inverse dynamic analysis, Gait Posture 39 (2014) 135–140.
[11] M.G. Browne, J.R. Franz, The independent effects of speed and propulsive force on joint power generation in walking, J. Biomech. 55 (2017) 48–55.
[12] J.B. Waanders, T. Hortobagyi, A. Murgia, P. Devita, J.R. Franz, Advanced age redistributes positive but not negative leg joint work during walking, Med. Sci. Sports Exerc. 51 (2019) 615–623.
[13] M.G. Browne, J.R. Franz, More push from your push-off: joint-level modifications to modulate propulsive forces in old age, PLoS One 13 (2018) 1–14.
[14] M.G. Browne, J.R. Franz, Ankle power biofeedback attenuates the distal-to-proximal redistribution in older adults, Gait Posture 71 (2019) 44–49.
[15] A.B. Gordon, M.L. McMulkin, B. Tompkins, P. Caskey, G.O. Baird, Gait findings in the adolescent subject with a stiff hip, J. Pediatr. Orthop. 33 (2013) 139–144.
[16] M.H. Schwartz, A. Rozumalski, The gait deviation index: a new comprehensive index of gait pathology, Gait Posture 28 (2008) 351–357.
[17] C.L. Romano, C. Frigo, G. Randelli, A. Pedotti, Analysis of the gait of adults who had residua of congenital dysplasia of the hip, J. Bone Joint Surg. Am. 78 (1996) 1468–1479.
[18] E.N. Pedersen, E.B. Simonsen, T. Alkjaer, K. Soballe, Walking pattern in adults with congenital hip dysplasia: 14 women examined by inverse dynamics, Acta Orthop. Scand. 75 (2004) 2–9.
[19] D.J. Sucato, K. Tulchin, M.W. Shrader, A. DeLaRocha, T. Gist, G. Sheu, Gait, hip strength and functional outcomes after a Ganz periacetabular osteotomy for adolescent hip dysplasia, J. Pediatr. Orthop. 30 (2010) 344–350.
[20] J.S. Jacobsen, D.B. Nielsen, H. Sorensen, K. Soballe, I. Mechlenburg, Changes in walking and running in patients with hip dysplasia, Acta Orthop. 84 (2013) 265–270.
[21] L.A. Karol, S.E. Halliday, P. Gourineni, Gait and function after intra-articular arthrodesis of the hip in adolescents, J. Bone Joint Surg. 82-A (2000) 561–569.
[22] R.B. Davis, S. Ounpuu, D. Tyburski, J.R. Gage, A gait analysis data collection and reduction technique, Hum. Mov. Sci. 10 (1991) 575–587.
[23] H.J. Woltring, A FORTRAN package for generalized cross-validatory spline smoothing and differentiation, Adv. Eng. Software. 8 (1986) 104–113.
[24] VICON FAQs Software, How Does Nexus (Plug-in Gait) and Polygon Calculate Gait Cycle Parameters (Spatial and Temporal)? (2019) (accessed 01 July 2019), https://www.vicon.com/faqs/software/how-does-nexus-plug-in-gait-and-polygon-calculate-gait-cycle-parameters-spatial-and-temporal.
[25] R. Baker, J.L. McGinley, M.H. Schwartz, S. Beynon, A. Rozumalski, H.K. Graham, O. Tirosh, The gait profile score and movement analysis profile, Gait Posture 30 (2009) 265–269.
[26] M.H. Schwartz, A. Rozumalski, R. Baker, A new method for computing the gait deviation index and clinical movement analysis, Proceedings of the Gait and Clinical Movement Analysis Society, Cincinnati, 2013.
[27] B.W. Stansfield, S.J. Hillman, M.E. Hazlewood, A.A. Lawson, A.M. Mann, I.R. Loudon, et al., Sagittal joint kinematics, moments and powers are predominantly characterized by speed of progression, not age, in normal children, J. Pediatr. Orthop. 21 (2001) 403–411.
[28] D.J. Farris, G.S. Sawicki, The mechanics and energetics of human walking and running: a joint level perspective, J. R. Soc. Interface 9 (2012) 110–118.
[29] J.S. Stebbins, M. Harrington, N. Thompson, A. Zavatsky, T. Theologis, Gait compensations caused by foot deformity in cerebral palsy, Gait Posture 32 (2010) 226–230.