Use of an IMU system to examine gait changes when altering alignment in a rotationplasty prosthesis

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Introduction

Rotationplasty is a reconstructive, limb-sparing option for management of lower extremity bone deficiency. Potential candidates for rotationplasty include, but are not limited to, patients with osteosarcoma localized to the distal femur or proximal tibia.[1] This technique involves a resection of the affected bone(s), followed by 180° rotation of the distal limb to allow the ankle to function as a knee joint when it is fit with a modified below-knee prosthesis.

With the rotationplasty procedure having been well-established for many years, there have been multiple studies investigating general gait and functional outcomes, particularly in comparison with other limb salvage or amputation procedures. These studies have reported favorable results with rotationplasty.[2,3,4] However, there are minimal studies which have specifically examined prosthesis design and its effect on gait or function. In a 2007 literature review, Fatone found eight studies that reported kinematics and kinetics following rotationplasty, however none of the studies provided a sufficiently detailed description of the prosthesis or alignment.[5] Traditionally, prosthetists have aimed for the rotated ankle to be positioned in maximum plantarflexion within the prosthesis.[6] This is likely due to both concern for cosmesis and for presumed mechanical advantage. There are, however, no quantifiable results to support this conventional alignment.

Clinical gait analysis has traditionally fallen into one of two extreme categories: observational and instrumented. Observational gait analysis is simple visual assessment by a trained observer and requires no special equipment, but it is limited to the observer's skill level and does not allow for quantifying abnormality. Instrumented gait analysis systems, such as three-dimensional (3D) motion capture systems, are widely-used and accurate, but are costly and not available in many clinical settings. As healthcare reimbursement increasingly relies on measureable outcomes, a need has arisen for a practical gait analysis system that offers both clinical simplicity and concrete data collection capability. In recent years, inertial measurement units (IMUs) have come to the market and opened the door for utilizing these wearable sensors in a clinical setting for gathering information on gait kinematics and spatio-temporal parameters without the need for complex equipment.

The aim of this study is two-fold: 1) to use an IMU system (iSen™ by STT Systems, San Sebastian, Spain) in a clinical setting to perform kinematic and spatio-temporal gait analysis, and 2) to examine the effect of rotated ankle ("pseudoknee") alignment within the prosthesis on gait. This is a study of a single pediatric patient who has undergone rotationplasty due to osteosarcoma.

Methods

Inclusion criteria were as follows: age 8 years or older, ability to ambulate up to 20 meters without assistive device, and history of rotationplasty due to osteosarcoma. An appropriate subject was identified from Children's Healthcare of Atlanta's pool of rotationplasty patients, and consent to participate was given by subject and parent. A chart review was performed using Children's electronic patient chart system (EPIC™ and Chartmaxx™). Chart review data consisted of demographics, history of the illness, physical exam findings, and length of follow up. A physical examination was performed on the day of data collection which included range of motion assessment and manual muscle testing of the affected limb. The subject was asked a series of questions related to activities of daily living and use of her current prosthesis.

A new prosthesis was fabricated for study purposes. Subject's affected limb was cast in 60° of ankle plantarflexion (30° pseudoknee flexion). Prosthesis was fabricated in the same manner as subject's own prosthesis. It included a leather thigh corset with anterior opening, an acrylic laminated foot socket, a pelite inner socket, and single axis steel joints (Otto Bock 7U2=R). A rigid foam was used between socket and lower components. Subject's own prosthesis includes a glass composite dynamic response foot, category 3 (Ability Dynamics Rush87™), but the study prosthesis included a lower-profile foot due to build height limitations (Ability Dynamics Rush81™). This foot was also a glass composite dynamic response foot, category 3. The overall weight of the study prosthesis was 2.1 kg, while the subject's own prosthesis weighed 2.7 kg.

Alignment conditions were 30°, 20°, 10°, and 0° of pseudoknee flexion (Fig. 1). The study prosthesis was adjusted between conditions by gradually filing down the extension stops of the steel joints until the appropriate flexion angle was achieved. Attachment foam was then cut, and the prosthetic foot was realigned to maintain the alignment relationship between the thigh section, mechanical joints, and prosthetic foot in all planes as best possible. Knee axis height was also maintained.

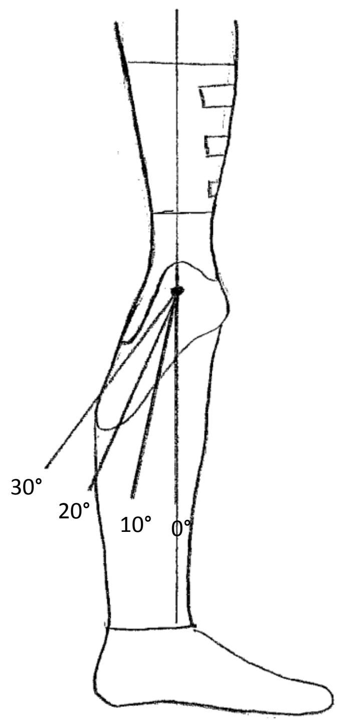


Figure 1. Alignment of rotated ankle in a rotationplasty prosthesis

The IMU system utilized was iSen™ by STT Systems, San Sebastian, Spain. The system consists of iSen™ 3.01 software and STT-IWS WiFi inertial sensors. Sensors contain a gyroscope, an accelerometer, and a magnetometer. Data was collected at 103 Hz. This study used iSen's lower train gait analysis protocol, which utilizes seven sensors and gathers kinematic and spatio-temporal data. The protocol dictates one sensor is placed on the posterior pelvis, and one on each thigh, calf, and foot.

A 12-meter walkway in a level hallway of a clinical treatment area was marked off. Sensors were positioned according to iSen protocol. Subject was asked to walk at a self-selected speed for each trial. For each of the four conditions (30°, 20°, 10°, 0°), the patient walked two lengths of the walkway prior to recording data for a period of acclimation. Three 12-meter passes for each condition were then recorded. The subject rested for a minimum of 45 minutes between conditions while the prosthesis was realigned. The subject provided verbal feedback on how each alignment felt. Analysis was limited to the middle 10 meters of the recorded data. Data from the three trials for each condition were averaged to examine trends with the exception of knee and hip kinematic plots which were generated by iSen. Additionally, three trials of the subject walking in her own prosthesis were recorded for comparison data. All data was collected in a single day within a 7-hour period.

Results

The study subject was a 14-year old female, with a weight of 49.7 kg and height of 160 cm. The subject was diagnosed July 2014 with osteosarcoma of the left distal femur. In October 2014, she underwent a left distal femur radical resection with rotationplasty reconstruction. She completed chemotherapy in

April 2015. She did have metastasis to the lungs and underwent bilateral thoracotomies in early 2015 and a left thoracotomy in October 2016. The subject received her first prosthesis in February 2015. She has received 3 additional prostheses since then, including a running prosthesis in November 2016. Her current everyday prosthesis has the socket aligned in 6° of pseudoknee flexion. She wears her prosthesis 12-16 hours per day.

The subject lives in a multilevel home with family. She is a very active teenager and recently has taken up track and field. She swims competitively, training or competing up to 4 times per week. The subject reports excellent ability to walk at variable speeds, on uneven surfaces, and on ramps and stairs when using her prosthesis. She reports overall excellent comfort and stability in her prosthesis. She does use a hand rail when descending stairs and reports tripping without falling about twice per week. On the day of data collection, the subject's left lower extremity strength measured 5/5 according to manual muscle testing. Left lower extremity ROM is listed in Table 1.

Table 1. Left lower extremity ROM

	Active ROM (°)	Passive ROM (°)
Pseudoknee flexion	100	110
Pseudoknee extension	-10	0
Hip extension	30	40
Hip flexion	115	145

Table 2 lists patient's subjective verbal feedback for each alignment condition.

Table 2. Subjective feedback

Socket Flexion Angle	Subject feedback
30°	Prosthesis feels comfortable Difficult to bear weight on toe of prosthetic foot Better suspension
20°	Still difficult to bear weight on toe of prosthetic foot Can achieve "double click" Liked 30° better
10°	Feels like "her" prosthesis Can bear weight on toe of prosthetic foot "I like this range and the first one's comfort (30°)"
0°	Too much stretch on ankle dorsum Difficult to achieve click Bearing weight on anatomical toes

Figures 2-5 illustrate average spatio-temporal data across the three trials for each socket alignment condition. Of the 4 study conditions, the subject exhibited highest cadence (50.8 steps/min), shortest step length (0.59 m), slowest speed (0.96 m/s), and least prosthesis stance time (56.3%) when the socket was set at 0° flexion. She exhibited the longest step length (0.64 m) and fastest speed (1.00 m/s) at 30° socket flexion. As the socket flexion angle decreased, stance time symmetry between sound limb and affected limb improved, with most symmetry at 0° socket flexion. Her own prosthesis performed comparably to the 0° condition in terms of spatio-temporal gait characteristics, with the exception of a much longer sound limb stance time (59.7% of gait cycle in stance with own prosthesis versus 53.4% with 0° condition).

Figure 2. Cadence

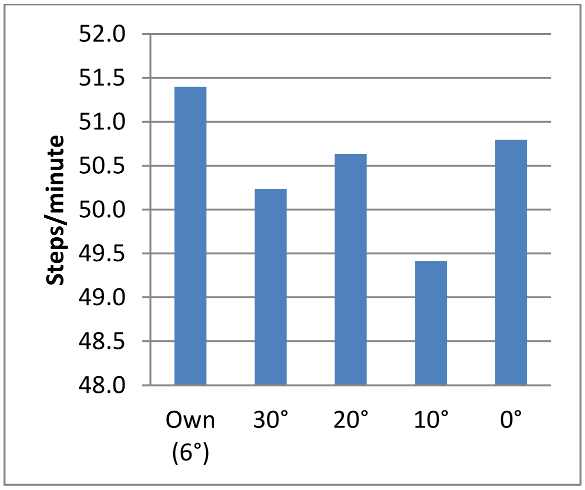


Figure 3. Step length

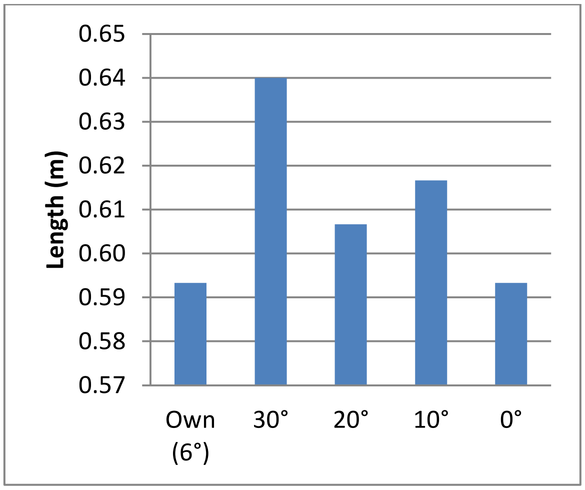


Figure 4. Speed

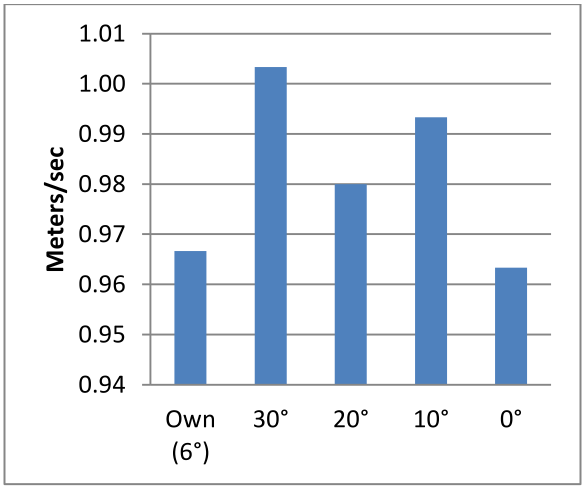
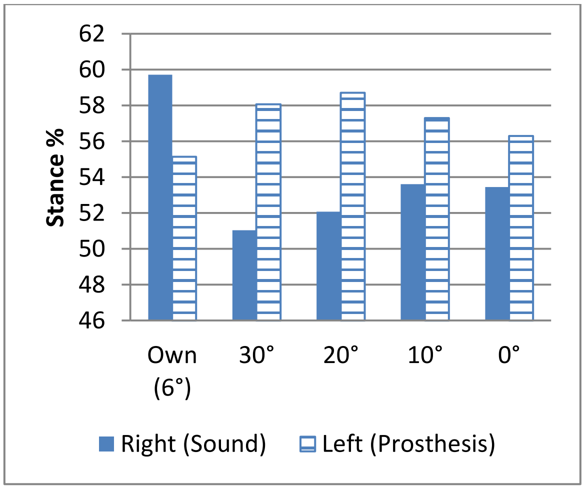


Figure 5. Stance time as % of gait cycle



Figures 6-8 illustrate average sagittal plane knee and hip kinematics across the three trials for each socket alignment condition. Under the 4 study conditions, the peak knee flexion angle on the prosthesis side increased with decreased socket flexion; maximum knee flexion was 67.6° at 0° socket flexion. Sound side and affected side were most symmetrical with respect to peak knee flexion under the 20° condition. Peak hip flexion angle on the prosthesis side was highest (45.9°) under the 30° condition, lowest (41.14°) under the 10° condition, and most closely matched the sound side under the 0° condition. Peak hip extension angle on the prosthesis side was greatest (34.5°) under the 10° condition. There was greater symmetry between prosthesis and sound sides in hip flexion than in hip extension. Overall hip ROM was greater for the prosthesis side than for the sound side under all conditions, including the subject's own prosthesis.

Figure 6. Peak knee flexion angle

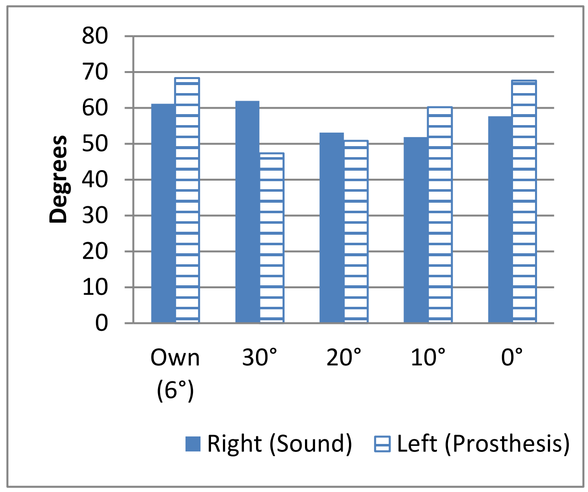


Figure 7. Peak hip flexion angle

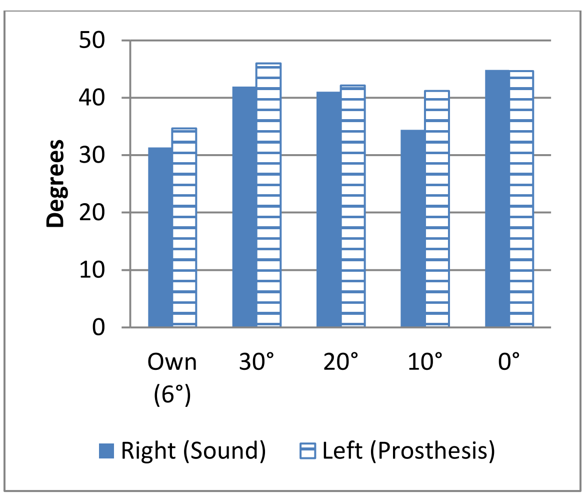


Figure 8. Peak hip extension angle

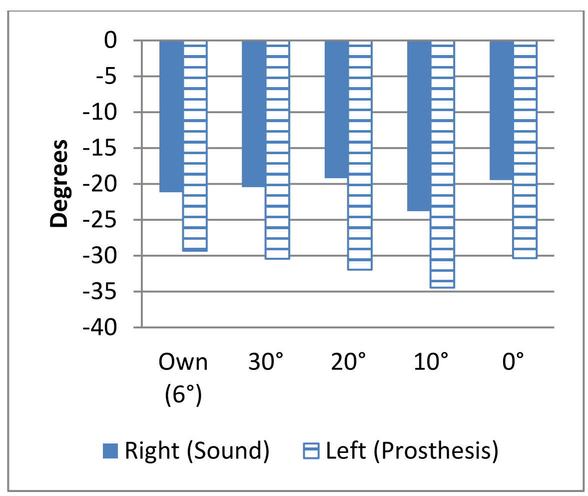


Figure 9. Knee and hip joint plots

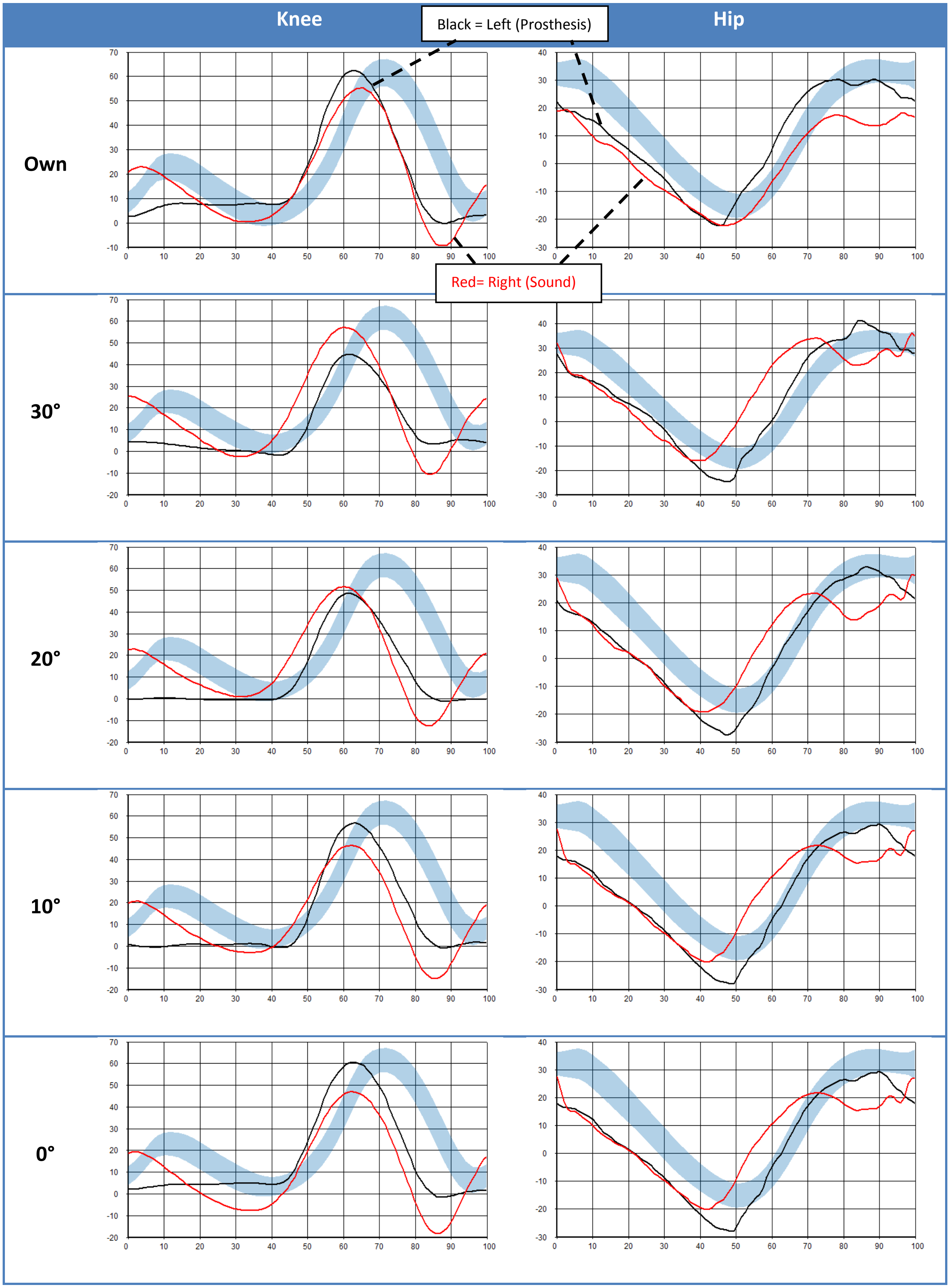


Figure 9 displays sagittal motion at the knee and hip joints throughout the gait cycle. These plots were generated directly by the iSen software, and each plot reflects a single representative trial from each of the alignment conditions. The shaded regions represent normative data. In all study conditions, there was minimal knee flexion (<10°) at loading response on the prosthesis side. The flexion/extension pattern of the prosthesis side during stance was most natural under the 30° study condition where very slight flexion is observed in loading response, with a return to full extension at terminal stance. The subject exhibited the most prosthesis stance phase knee flexion and overall better knee flexion/extension symmetry in her own prosthesis as compared to the 4 study conditions. Likewise, she exhibited an overall more symmetrical hip flexion/extension pattern when wearing her own prosthesis than when under any of the 4 study conditions. Under all conditions, including patient's own prosthesis, there was an obvious deviation from the norm in the sagittal hip motion at around 70% of the gait cycle, where the plot indicates that during midswing of the sound side, there is a quick hip extension motion of the sound side followed by a return to flexion.

Discussion

The iSen system proved to be simple and efficient to use in a clinical setting. The careful realignment of the study prosthesis between conditions was by far the more time-consuming portion of the study methods. Once the sensors and router were set up at the start of the day, it was quick and straightforward to position the sensors and collect data for each condition and trial. It is recommended that the iSen system be validated against a gold standard instrumented gait analysis system to ensure reliability of results. The iSen system and other IMU systems, however, seem to be a useful tool for quantifying outcomes in a clinical setting.

Spatio-temporal data in this study is comparable to that of other rotationplasty gait studies[7,8,9,10], with the exception of the subject in this study exhibiting a longer stance phase on the affected side than on the sound side. The knee kinematic data in this study is largely comparable to that of other rotationplasty gait studies as well, particularly regarding reduced knee flexion on the prosthesis side during loading response and stance.[8,10,11] The hip kinematics data in this study, however, differed from other studies in terms of the unusual sound side hip extension at what seems to be midswing of the sound side. It is speculated that this burst of apparent hip extension is actually posterior pelvic tilt to put her affected side's hip flexors on stretch in preparation for toeoff of the prosthesis side. This may indicate the need for patients who have undergone rotationplasty to focus on strengthening the hip flexors of the affected side for improved kinematic symmetry.

One limitation of this study is the inability to truly compare the study conditions to the subject's own prosthesis due to a weight difference of 0.6 kg between the prostheses as well as use of a different model prosthetic foot. The subject's prosthetic foot (Rush87) has a longer/taller keel with greater flexibility than the study prosthesis foot (Rush81). These differences could potentially influence both the spatio-temporal data and the kinematic data.

In terms of this study's single subject, there is no clear-cut finding that indicates the traditional goal of 0° of socket flexion is ideal for optimal gait, which is cause for further investigation. It is recommended that this study be replicated with more subjects. Future studies might include EMG analysis and kinetic analysis to determine the optimal socket alignment as it relates to muscle activity and strength. Likewise, this study method is a useful starting place for further studies which use an IMU system to determine the impact of any number of prosthesis aspects (prosthetic foot model, fabrication materials, socket design, etc.) on gait outcomes.

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