The Effect of Passive Prosthetic Feet on the Performance of Activities of Daily Living: A Preliminary Investigation

By

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Chapter I

INTRODUCTION

1.1 Ankle and Toe Joint Range of Motion in Activities of Daily Living

A varying degree of ankle and toe joint range of motion (ROM) is involved in performing activities of daily living (ADL), such as walking, sitting, and reaching [1]. Reduced or limited ROM (flexion/extension) in these areas can lead to a diminished ability to complete these tasks [1]. One group of the population that is largely affected by this issue is lower-limb prosthetic device users (PDUs).

Most commercially available ankle-foot prostheses are rigid, passive devices that lack many of the mechanical characteristics of a biological foot and ankle [2]. PDUs typically use protheses that are minimally flexible or completely fixed at the ankle. Additionally, very few available protheses incorporate a flexible toe joint, which has been shown to make a significant contribution to locomotion and performance of ADL [3]. These mechanical deficits have been widely studied in the context of walking and running gait [3, 4, 5]; however, a knowledge gap exists in the study and characterization of PDUs performing daily tasks.

1.2 Limitations in Existing Scientific Literature

An extensive study was conducted to collect information on PDUs' ability to perform numerous tasks that are deemed necessary for daily living [6]. This study reported that 11% of prosthesis users cannot stand up from a chair, 25% cannot pick an item up off the floor, and 40% cannot move without assistance during daily tasks [6]. These results emphasize that PDUs struggle to perform basic ADL, but they do not address the differences that exist in their biomechanics and movement patterns when compared to able-bodied individuals.

Limited research has studied the sit-to-stand movement of PDUs compared to able-bodied individuals. These studies reported significant asymmetrical loading between limbs in PDUs, with increased loading on the intact limb versus the prosthetic limb [7, 8]. Negative implications associated with this asymmetry include risks of overuse injuries and joint degeneration [9]. With sit-to-stand being one of the only movement patterns that has been biomechanically characterized in scientific literature, there is a need to study additional functional movements necessary for independent living.

The purpose of this study is to identify the various deficits and differences PDUs have when performing ADL in their prescribed passive ankle-foot by comparing their movement to a healthy control group. This information will help build a foundation for potential interventions for these issues in the future, such as a new approach to device design.

Chapter II

METHODS

2.1 Participant Recruitment

Three individuals with below-knee (transtibial) limb loss were recruited for this study. Individual and mean demographics are presented in **Table 1**. (*N*=3; age: 35.3 ±11.8 years; body mass: 92.3±11.5 kg; height: 1.79±0.05 m; mean±standard deviation). Two active, able-bodied control (ABC) participants were also recruited for this study (*N*=2; age: 28.0 ±2.00 years; body mass: 85.0±9.45 kg; height: 1.80±0.05 m; mean±standard deviation). Two of the three PDUs were gender, age, height, and weight-matched with the ABC group. This is an ongoing study and additional participants are being actively recruited. Each participant's specifications are further detailed in **Table 1** and **Table 2**. All five participants included in this study are male, and all PDUs are left-side amputees. All data collection for this study took place at Vanderbilt University, after each participant provided informed consent, which was approved by the Institutional Review Board at Vanderbilt University.

Participant ID	Age (years)	Body mass (kg)	Height (m)	Gender	K-level	Cause of limb loss	Daily-use prosthesis
S01	28	97.8	1.78	M	4	Trauma	Fillauer AllPro
S02	26	76.2	1.74	M	4	Trauma	Fillauer AllPro
S03	52	102.8	1.86	M	4	Trauma	Fillauer AllPro
Mean +/- SD	35.3 ± 11.8	92.3 ± 11.5	1.79 ± 0.05				

Table 1 Summary of PDU participant demographics.

Participant ID	Age (years)	Body mass (kg)	Height (m)	Gender
S01	30	94.4	1.85	M
S02	26	75.5	1.75	M
Mean +/- SD	28.0 ± 2.00	85.0 ± 9.45	1.80 ± 0.05	

Table 2 Summary of ABC participant demographics.

2.2 Data Collection Protocol

Each participant in both groups (PDU and ABC) separately attended one data collection session. The PDUs wore their prescribed passive device, specified in **Table 1**. All participants were shod during data collection. At the beginning of the testing session, a set of retro-reflective markers were placed on the participant's pelvis (6), back (6), thighs (8), knees (4), ankles (4), shank (8), and feet (16) (**Figure 1**). Particular attention was paid to the foot markers in this study to be able to accurately measure the range of motion of the metatarsophalangeal (toe) joint. This marker set includes three calcaneus (heel) markers, a marker on the second toe, a marker on the first and fifth metatarsal head, as well as a marker on the first and fifth metatarsal base (**Figure 2**).

Figure 1. Placement of full-body markers on a PDU from the anterior and posterior (A and B respectively).

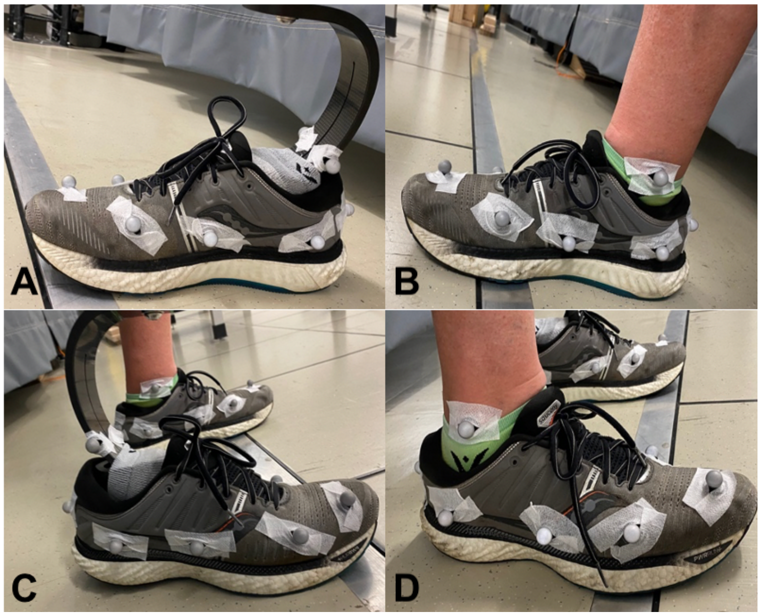

Figure 2. Placement of foot and ankle markers on a PDU showing medial views of both feet (A and B) and lateral views of both feet (C and D).

All data were collected using a three-dimensional motion capture system (200 Hz; 10-camera system, Vicon, Oxford, UK) and six in-ground force-plates (1000 Hz; three-by-two grid arrangement AMTI, Watertown, USA). A static (standing) trial of each participant was collected, followed by functional ankle, knee, and hip trials. The tasks for this study were chosen based on feedback from local PDUs, physicians, and prosthetists, as well as scientific literature [10]. All tasks included are sitting down in a chair and standing back up (sit-to-stand), reaching to pick an object up off the floor, lifting a box from the floor, squatting, and lunging. Details about each exercise, as well as the able-bodied equivalent can be found in **Table 3**. Each separate activity was performed three times in a single trial. Following the completion of each task, participants were asked to rate their effort, stability, and comfort level on a scale of 0 to 10.

PDU ADL	ABC ADL
Sit-to-stand- average chair height (48 cm)	**Sit-to-stand**- average chair height (48 cm)
Sit-to-stand- low chair height (38 cm)	Sit-to-stand- low chair height (38 cm)
Sit-to-stand- lowest chair height (28 cm)	Sit-to-stand- lowest chair height (28 cm)
Reaching to pick an item up off the floor- prosthetic leg leading	**Reaching** to pick an item up off the floor- nondominant leg leading
Reaching to pick an item up off the floor- intact leg leading	Reaching to pick an item up off the floor- dominant leg leading
Lifting a 10kg box from the floor- box in-front of participant	**Lifting** a 10kg box from the floor- box in-front of participant
Lifting a 10kg box from the floor- box to the left of participant	Lifting a 10kg box from the floor- box to the left of participant
Lifting a 10kg box from the floor- box to the right of participant	Lifting a 10kg box from the floor- box to the right of participant
Squatting	**Squatting**
Lunging – prosthetic leg leading	**Lunging** – nondominant leg leading
Lunging- intact leg leading	Lunging- dominant leg leading

Table 3. List of the activities of daily living performed by each group.

2.3 Data Processing and Analysis

Marker trajectories and ground reaction force data were low-pass filtered at 8 Hz and 15 Hz, respectively, with a fourth order Butterworth filter. Joint angles were computed in the sagittal plane through Visual 3D software (C-motion, Germantown, MD, USA), and exported into MATLAB (MathWorks, Natick, USA) where additional processing took place. The outcome metrics reported in this study include vertical ground reaction force (vGRF), normalized to each participant's body weight, and ankle and toe ROM, computed as the total change in angle (in degrees) between the minimum and maximum peaks throughout the tasks.

Because this study is a preliminary investigation, not all versions of each task are presented in the results. The specific tasks shown in the results are sit-to-stand from the highest and lowest chair, lifting from the center, squatting, reaching for an object (one for each leg leading), and lunging (one for each leg leading). These are currently considered the primary tasks of interest moving forward in the study.

In addition, a specific portion of each task was reported as an initial analysis of possible outcomes to focus on. The sit-to-stand movement was shown as the instance the participant began standing from a sitting position and ended when the participant had stood all the way up and was fully upright. The portion of the lifting task that was reported in the results began when the box was lifted off the ground and ended when the participant was standing fully upright with the box in-hand. The squat was measured from the initial standing position to the final standing position. In other words, the lowest point of the squat is the midpoint of the task. The reaching task was reported from the initial standing position to the moment the participant picks up the object. Finally, the full cycle of the lunge was measured. That is, from initial standing position to final standing position, with the midpoint of the task being the lowest point in the lunge. As mentioned previously, three repetitions of each task were done in a single trial. The numbers presented in the results are the average of the three repetitions.

Chapter III

RESULTS

3.1 Task Completion and Rate of Perceived Exertion

Due to the fact that all PDUs were K4-level, all three PDU participants and all ABCs were able to complete every task independently. Based on the survey results, PDUs consistently found that standing up from the lowest chair (28 cm) required more effort and felt less stable and comfortable than the higher chair (48 cm). They additionally all rated lunging forward with their prosthetic leg as less stable and requiring more effort than lunging forward with their intact leg. On the other hand, both ABCs rated all tasks as very low effort and very high comfort and stability.

3.2 Vertical Ground Reaction Force (vGRF)

The timeseries plots in **Figure 3** show vGRF from one representative participant in each group. There was a noticeable difference in vGRF between legs in the PDU throughout the completion of tasks, and little difference between legs in the ABC (**Figure 3**). This shows that the PDU participant loaded more of his weight on his biological (intact) leg than his prosthetic. This trend was consistent across all PDU participants. It is also important to note that the PDU and ABC did take different amounts if time to complete certain tasks, which can be seen in **Figure 3**, as the peak vGRF was earlier in the ABC than the PDU for some tasks.

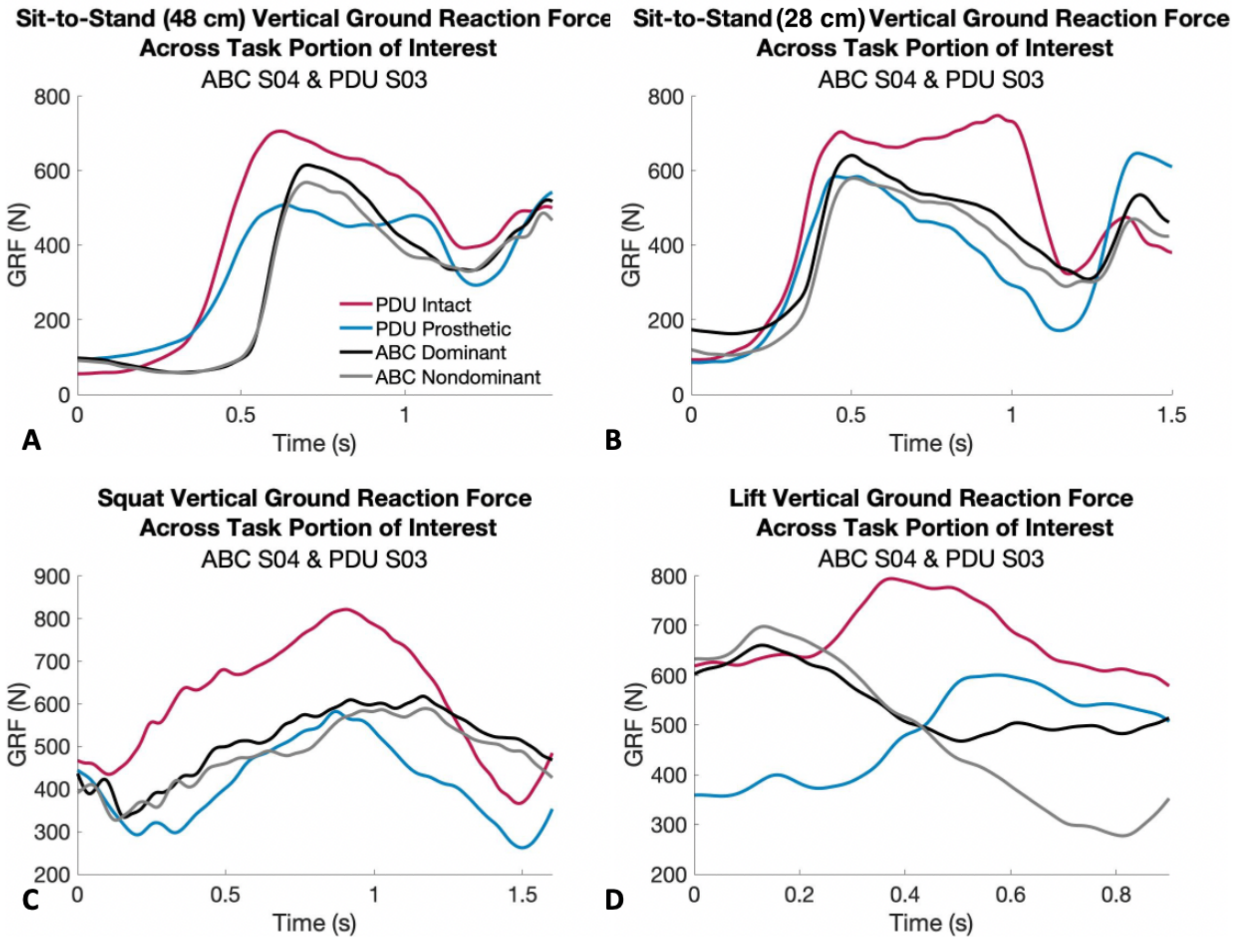

Figure 3. Representative vertical ground reaction force timeseries plots of a single repetition of each task. One PDU and one ABC were chosen to represent these results.

Similarly, there was an apparent difference in vGRF between legs in PDUs, as seen in **Figure 4**. Note that although the ABCs had very similar loading between legs, there are still some slight asymmetries that exist. When compared to the ABC group, all three PDUs had a much higher percent difference in vGRF between legs in both sit-to-stand tasks and the squat (**Figure 5**). Percent difference refers to difference between the dominant/intact and the nondominant/prosthetic limbs. Therefore, a positive percentage indicates more vGRF in the dominant/intact limb and vice versa. Percent difference in ankle and toe ROM follow this same convention.

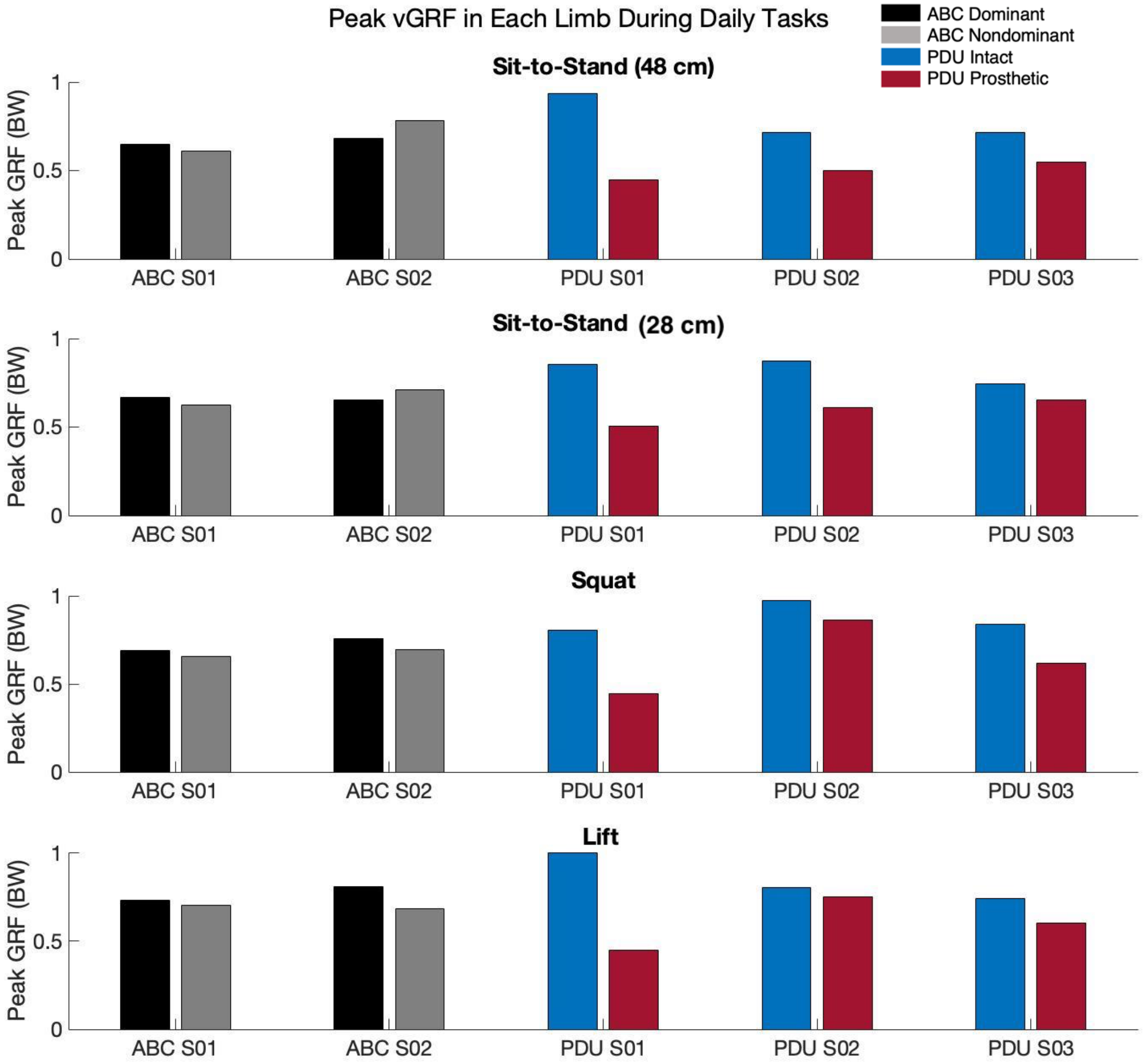

Figure 4. Average peak vertical ground reaction force, normalized by each participant's body weight.

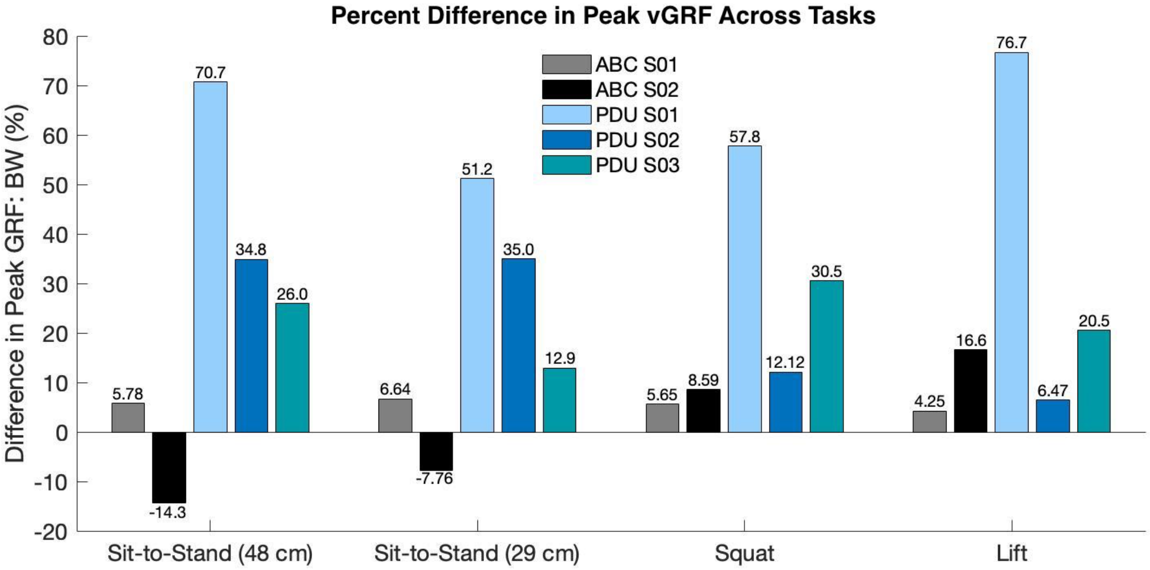

Figure 5. Computed difference in vertical ground reaction force between dominant/intact leg and nondominant/prosthetic leg for all participants during various tasks.

3.3 Ankle Range of Motion

The timeseries plots in **Figure 6** show ankle angle from one representative participant in each group. The ankle angle throughout the tasks consistently shows a considerable difference in ROM between the intact and prosthetic limb of the PDU, while the dominant and nondominant limbs of the ABC remain similar throughout. This indicates asymmetry in ankle ROM in PDUs during symmetric tasks (panels A-D). It is important to note that panel E-H below show the timeseries for asymmetrical tasks (reaching and lunging). The limb specified in the title refers to the leading leg during the tasks. Therefore, the timeseries plots will not follow the same patterns as panels (A-D). These four tasks were interpreted based on leg position. For example, the ankle angle of the back leg during a lunge with the dominant/intact leg leading was compared to the ankle angle of the back leg during a lunge with the nondominant/prosthetic leg leading.

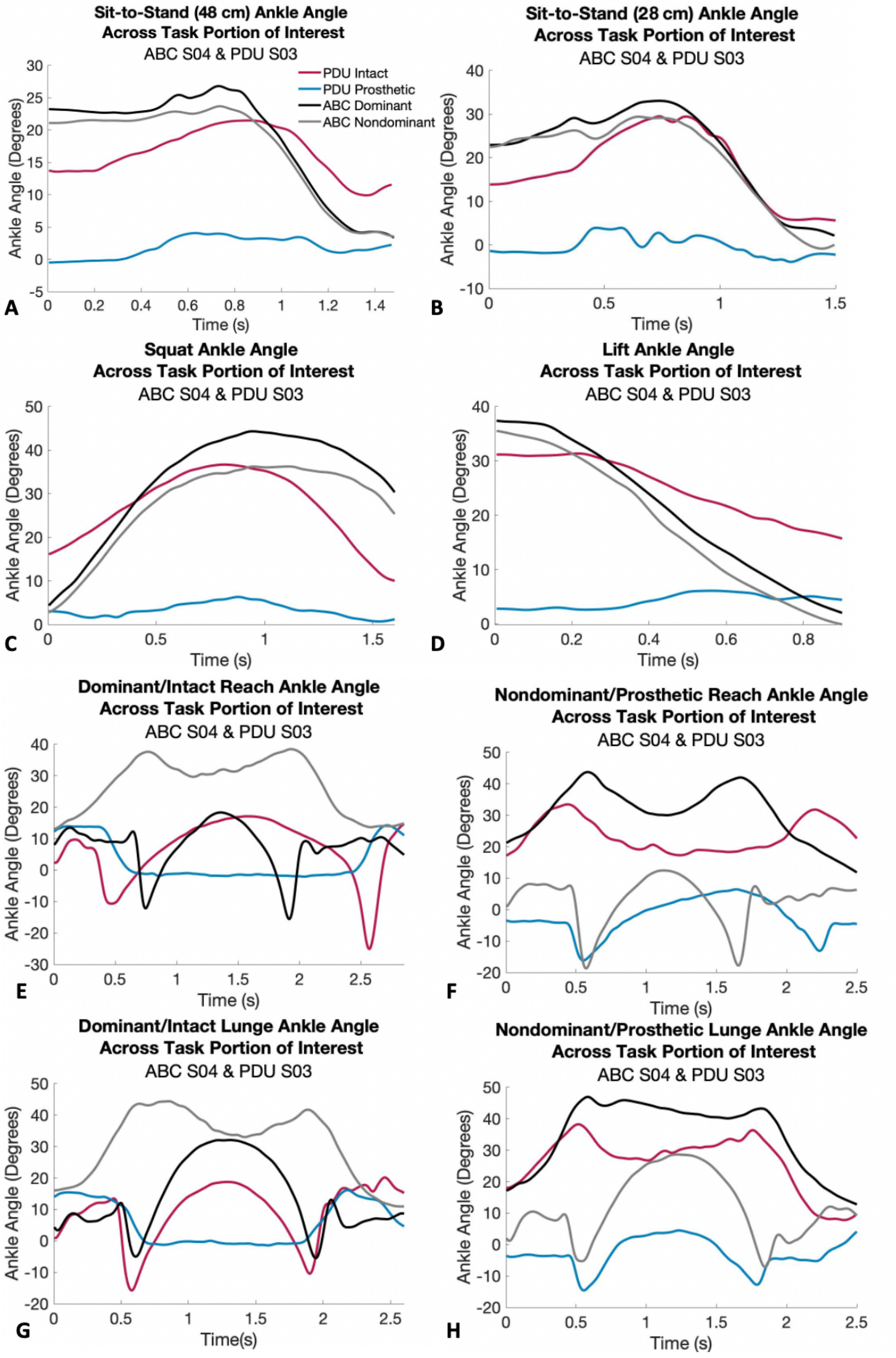

Figure 6. Representative ankle angle timeseries plots of a single repetition of each task. One PDU and one ABC were chosen to represent these results.

The average ankle range of motion in all tasks (**Figure 7**) shows appreciable between-limb differences in PDUs. In addition, ABCs during symmetrical tasks (sit-to-stand, lifting, and squatting) have an overall greater ankle ROM than PDUs. This trend is also depicted in **Figure 8** and **Figure 9**.

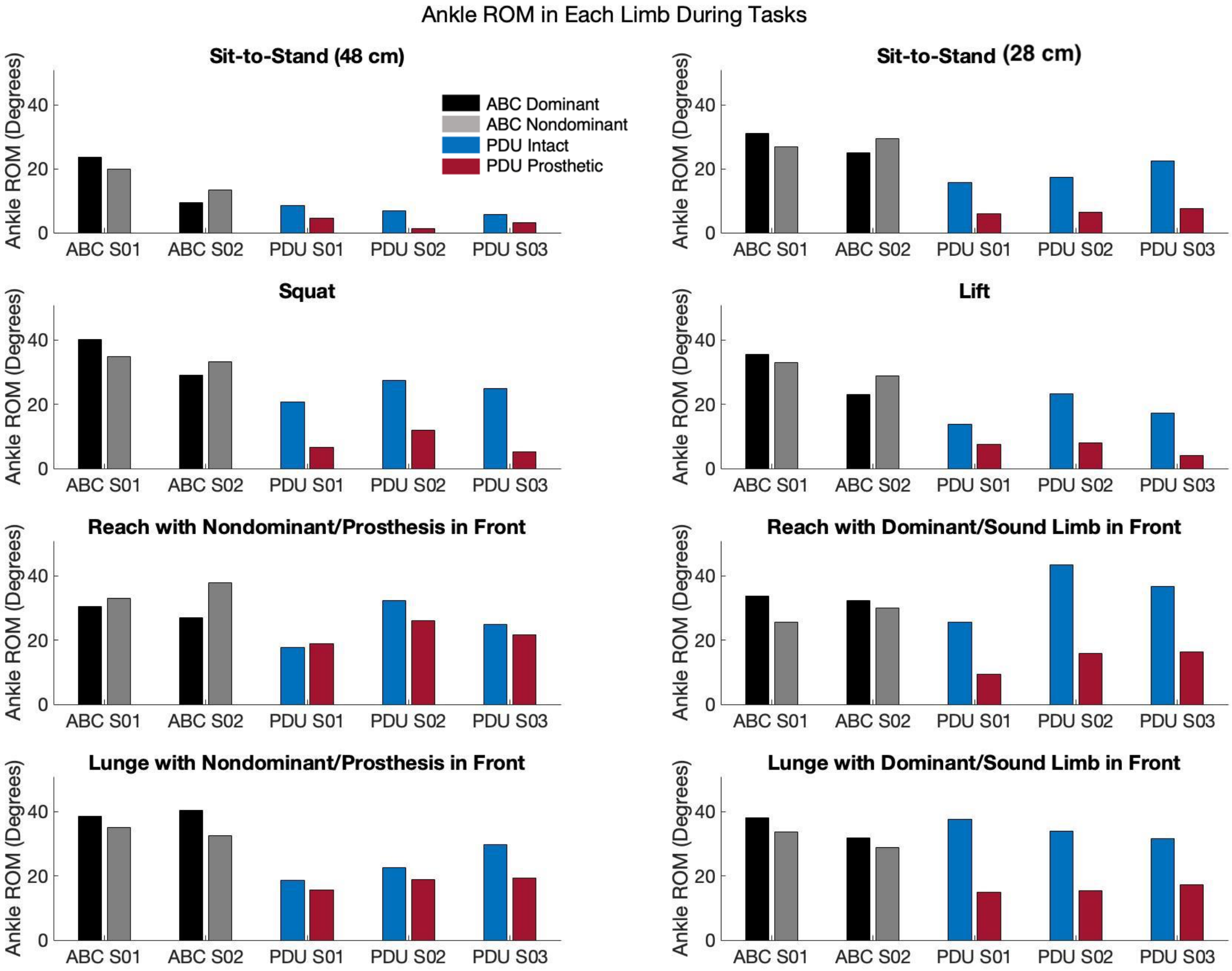

Figure 7. Average ankle ROM for all tasks.

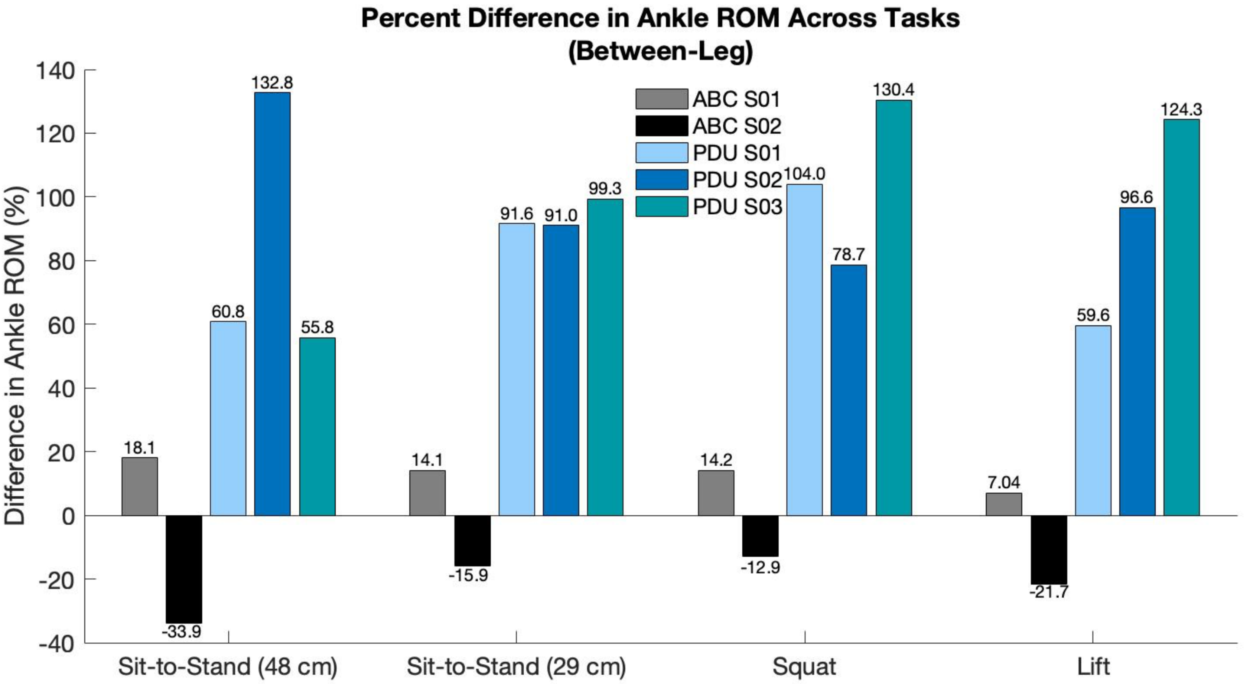

Figure 8. Computed difference in ankle ROM between dominant/intact leg and nondominant/prosthetic leg for all participants during various tasks.

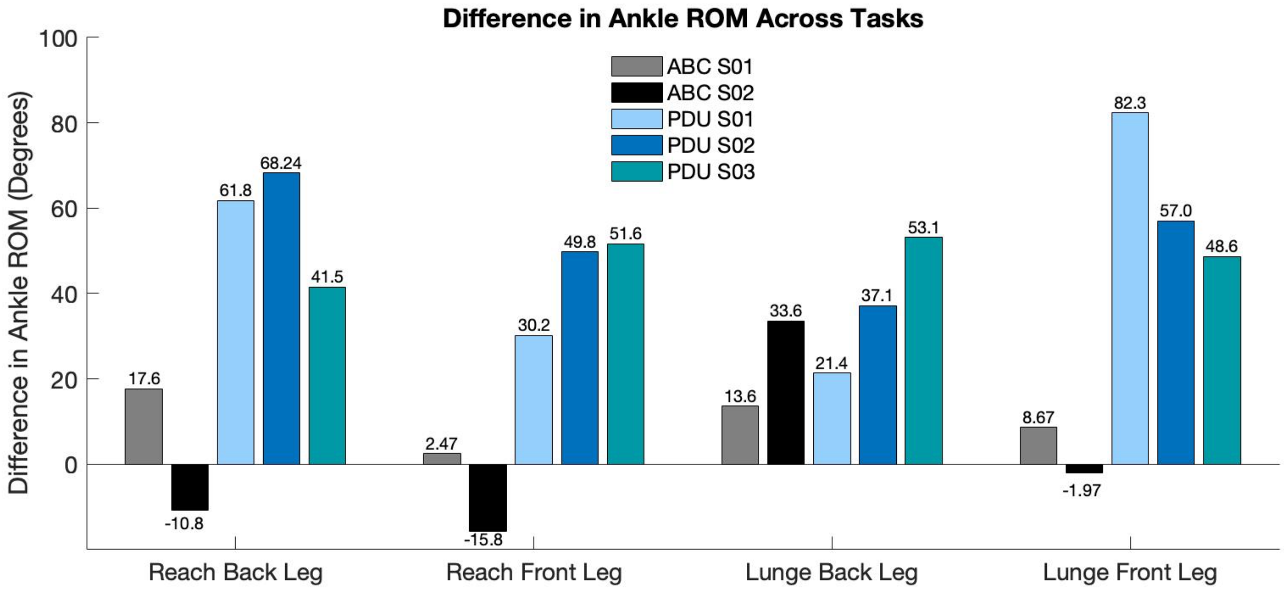

Figure 9. Computed difference in ankle ROM between dominant and nondominant legs while in the same position (i.e. front or back) and intact and prosthetic legs while in the same position.

3.4 Metatarsophalangeal (Toe) Joint Range of Motion

Toe ROM was reported for only asymmetrical tasks, as these tasks utilize toe flexion much more than symmetrical, “flat-footed” tasks, such as squatting and lifting. In addition, feedback from PDUs pointed out that these asymmetrical tasks are more challenging due to the absence of a toe joint on the prosthetic side. Similar to what was seen in ankle ROM, the toe angle throughout the tasks consistently shows a considerable difference in ROM between the intact and prosthetic limb of the PDU (when comparing legs in the same position), while the dominant and nondominant limbs of the ABC remain similar throughout. **Figure 12** shows percent difference between dominant/intact and nondominant/prosthetic based on leg position. Percent difference in toe ROM, similar to ankle ROM, was generally greater in PDUs than ABCs. Note that toe ROM was not reported for PDU S01, as toe data was not collected for this participant.

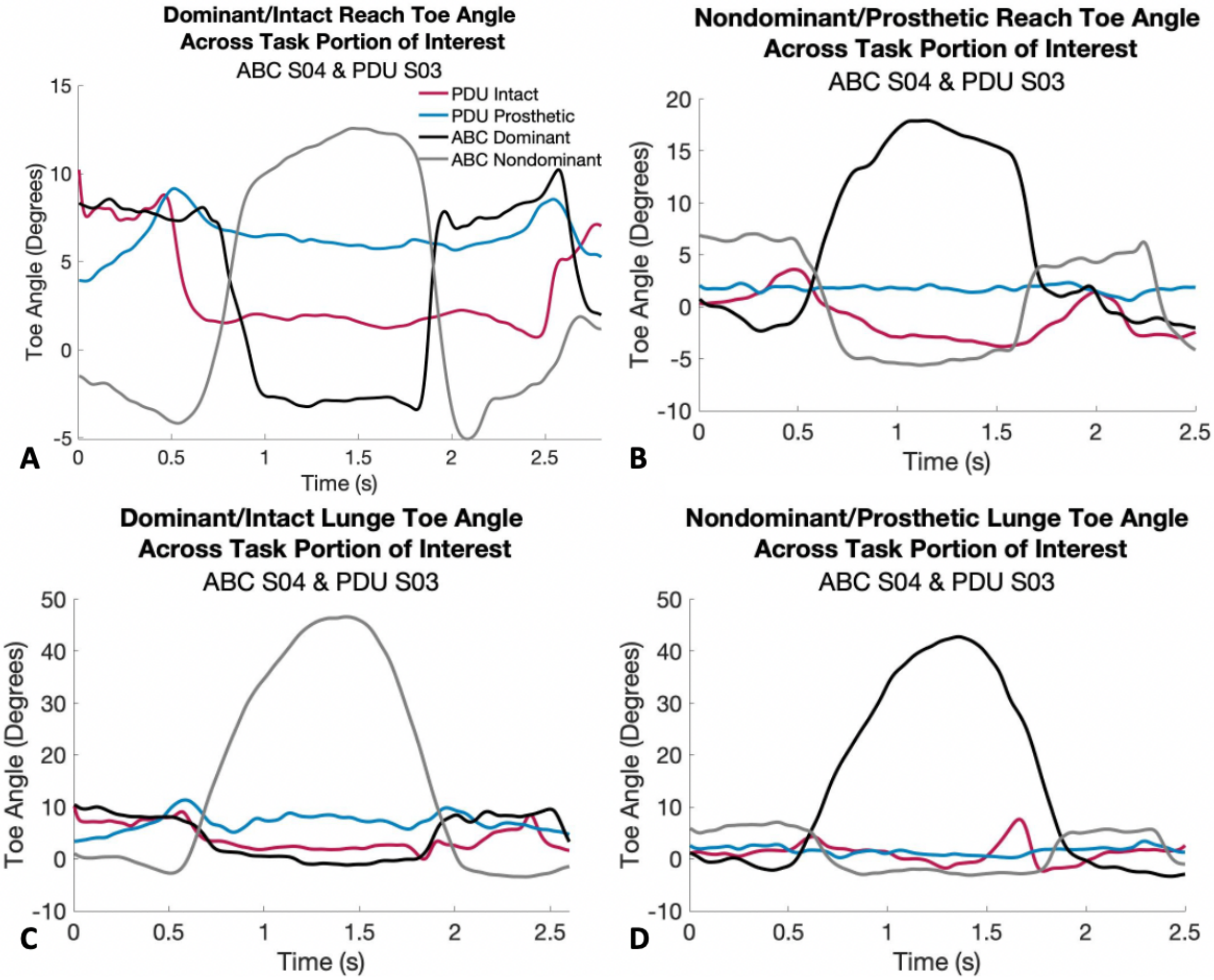

Figure 10. Representative toe angle timeseries plots of a single repetition of each task. One PDU and one ABC were chosen to represent these results.

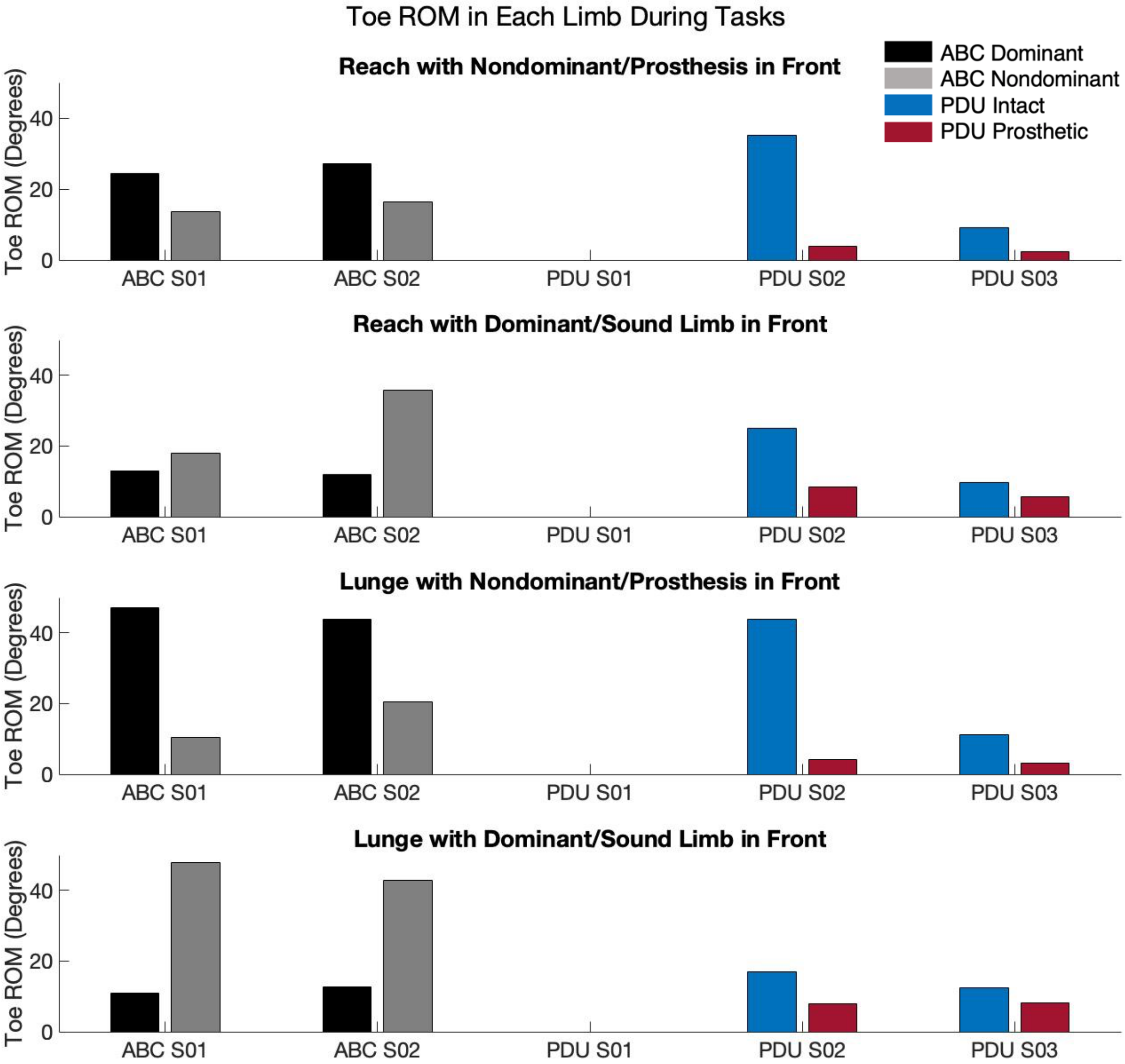

Figure 11. Average toe ROM for various tasks.

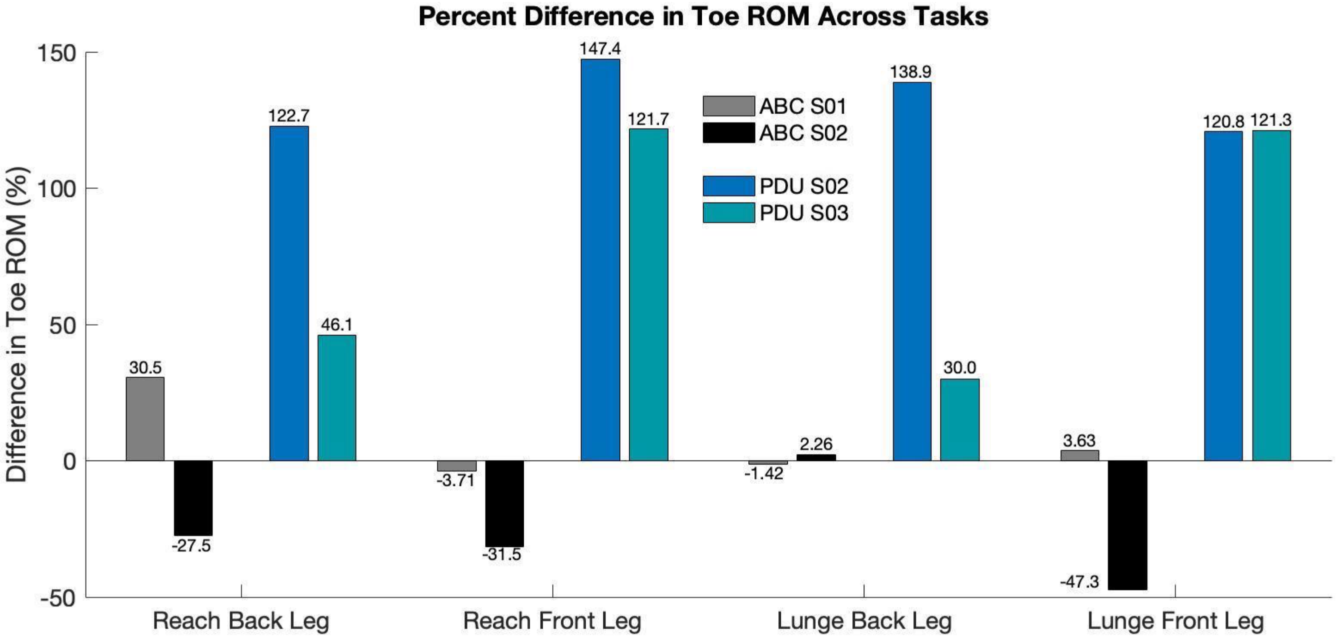

Figure 12. Computed difference in toe ROM between dominant and nondominant legs while in the same position (i.e. front or back) and intact and prosthetic legs while in the same position.

Chapter IV

DISCUSSION

4.1 Overview of Ground Reaction Force and Ankle and Toe Range of Motion

In all tasks reported, all PDUs loaded more weight on their intact limb than their prosthetic and two of the three PDUs had a higher difference between legs when compared to the ABCs. One major risk of long-term prosthesis use is the development of secondary conditions due to asymmetrical loading [11]. This includes joint degeneration, pain, and diseases such as osteoarthritis, back pain, and osteopenia [11]. These asymmetries were clear in the vGRF results.

All PDUs showed a greater ankle ROM on the intact side across tasks. This asymmetry suggests deficits on the prosthetic side that could be addressed in new devices by placing more emphasis on joint ROM. Similar results were seen in the tasks reported for toe ROM.

4.5 Importance and Future Work

The differences in ROM between the ABCs and PDUs, as well as the between-limb differences in PDUs, asserts the need to address and rethink how prosthetic devices impact daily life. These results may be used to better inform prosthetic device design, with performance of ADL in mind.

This information may allow for future device design to focus on modifying ankle and toe dynamics to benefit PDUs. Current work being done at Vanderbilt University that aims address many of the deficits shown previously includes a powered ankle intervention, called the Vanderbilt Powered Ankle. This device is shown to increase ankle push-off, ankle range of motion, and knee range of motion in the amputated limb [12]. The Vanderbilt Powered Ankle is an example of a device that emphasizes aspects of ankle and toe dynamics and has promising potential to serve as an intervention for PDUs.

4.6 Limitations

The main limitations of this study relate to participant recruitment. The small sample size limited this study to only males, all under the age of 55. Additionally, all PDUs in this study are K4-level. This means that they are highly active and exercise regularly. Because this influences the participants' performance of activities during data collection, the results could be more representative of deficits that exist in PDUs of similar K-level and may not reflect those of less-active PDUs. Future work should investigate the functional abilities and biomechanics of less active PDUs. As previously mentioned, the participants in this study were relatively young. The outcomes from this study do not account for elderly PDUs, which make up a large portion of individuals with limb loss. In 2005, elderly individuals (65+) made up for 42% of amputees, with rates of amputation increasing since [13]. Studying elderly prosthetic device users is an important future direction for this area of research.

Because this study aimed to capture the natural movement patterns of PDUs, they wore shoes they felt most comfortable in, as it is common for PDUs to choose a particular shoe that work best with their device. All participants in this study wore some form of athletic shoe. Different athletic shoes have varying heel-to-toe drops, which affect the foot-ground angle [14]. As a result, variations in shoe type could slightly alter the participant's range of motion during each task.

4.7 Conclusion

In closing, this study characterized the deficits and between-limb differences of PDUs wearing their prescribed passive device. When compared to able-bodied individuals, PDUs exhibited a higher degree of asymmetric loading, revealed through ground reaction force, while performing all tasks. In addition, PDUs consistently demonstrated a reduced ankle and toe range of motion compared to both their sound limb and able-bodied participants. This preliminary investigation provides interesting benchmark data that, with ongoing data collection, will help fill the knowledge gap discussed previously and better inform prosthetic device design.

REFERENCES

[1] K. Hyodo, T. Masuda, J. Aizawa, T. Jinno, and S. Morita, “Hip, knee, and ankle kinematics during activities of daily living: A cross-sectional study,” *Brazilian Journal of Physical Therapy*, vol. 21, no. 3, pp. 159–166, 2017.

[2] S. K. Au, J. Weber, and H. Herr, “Powered ankle--foot prosthesis improves walking metabolic economy,” *IEEE Transactions on Robotics*, vol. 25, no. 1, pp. 51–66, 2009.

[3] E. C. Honert, G. Bastas, and K. E. Zelik, “Effect of toe joint stiffness and toe shape on walking biomechanics,” *Bioinspiration & Biomimetics*, vol. 13, no. 6, p. 066007, 2018.

[4] K. A. McDonald, R. H. Teater, J. P. Cruz, J. T. Kerr, G. Bastas, and K. E. Zelik, “Adding a toe joint to a prosthesis: Walking biomechanics, Energetics, and preference of individuals with unilateral below-knee limb loss,” *Scientific Reports*, vol. 11, no. 1, 2021.

[5] M. Grimmer, M. Holgate, R. Holgate, A. Boehler, J. Ward, K. Hollander, T. Sugar, and A. Seyfarth, “A powered prosthetic ankle joint for walking and running,” *BioMedical Engineering OnLine*, vol. 15, no. S3, 2016.

[6] C. Gauthier-Gagnon, M.-C. Grisé, and D. Potvin, “Enabling factors related to prosthetic use by people with transtibial and transfemoral amputation,” *Archives of Physical Medicine and Rehabilitation*, vol. 80, no. 6, pp. 706–713, 1999.

[7] V. Agrawal, R. Gailey, I. Gaunaurd, R. Gailey, and C. O'Toole, “Weight distribution symmetry during the sit-to-stand movement of unilateral transtibial amputees,” *Ergonomics*, vol. 54, no. 7, pp. 656–664, 2011.

[8] M. J. Highsmith, J. T. Kahle, S. L. Carey, D. J. Lura, R. V. Dubey, K. R. Csavina, and W. S. Quillen, “Kinetic asymmetry in transfemoral amputees while performing sit to stand and stand to sit movements,” *Gait & Posture*, vol. 34, no. 1, pp. 86–91, 2011.

[9] A. M. Simon, N. P. Fey, K. A. Ingraham, S. B. Finucane, E. G. Halsne, and L. J. Hargrove, “Improved weight-bearing symmetry for transfemoral amputees during standing up and sitting down with a powered knee-ankle prosthesis,” *Archives of Physical Medicine and Rehabilitation*, vol. 97, no. 7, pp. 1100–1106, 2016.

[10] B. J. Hafner, S. J. Morgan, D. C. Abrahamson, and D. Amtmann, “Characterizing mobility from the Prosthetic Limb User’s perspective,” *Prosthetics & Orthotics International*, vol. 40, no. 5, pp. 582–590, 2016.

[11] R. Gailey, “Review of secondary physical conditions associated with lower-limb amputation and long-term prosthesis use,” *The Journal of Rehabilitation Research and Development*, vol. 45, no. 1, pp. 15–30, 2008.

[12] A. H. Shultz, B. E. Lawson, and M. Goldfarb, “Variable cadence walking and ground adaptive standing with a powered ankle prosthesis,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 24, no. 4, pp. 495–505, 2016.

[13] K. Ziegler-Graham, E. J. MacKenzie, P. L. Ephraim, T. G. Travison, and R. Brookmeyer, “Estimating the prevalence of limb loss in the United States: 2005 to 2050,” *Archives of Physical Medicine and Rehabilitation*, vol. 89, no. 3, pp. 422–429, 2008.

[14] L. Malisoux, N. Chambon, A. Urhausen, and D. Theisen, “Influence of the heel-to-toe drop of standard cushioned running shoes on injury risk in leisure-time runners,” *The American Journal of Sports Medicine*, vol. 44, no. 11, pp. 2933–2940, 2016.