Journal of Applied Biomechanics, 2023, 39, 403-414
https://doi.org/10.1123/jab.2023-0013

Human Kinetics
ORIGINAL RESEARCH

The Influence of Multiple Pregnancies on Gait Asymmetry: A Case Study

Aude S. Lefranc,[1] Glenn K. Klute,[2,3] and Richard R. Neptune[1]
[1]Walker Department of Mechanical Engineering, The University of Texas at Austin, Austin, TX, USA; [2]Department of Veteran Affairs, Center for Limb Loss and MoBility, Seattle, WA, USA; [3]Department of Mechanical Engineering, University of Washington, Seattle, WA, USA

Gait asymmetry is a predictor of fall risk and may contribute to increased falls during pregnancy. Previous work indicates that pregnant women experience asymmetric joint laxity and pelvic tilt during standing and asymmetric joint moments and angles during walking. How these changes translate to other measures of gait asymmetry remains unclear. Thus, the purpose of this case study was to determine the relationships between pregnancy progression, subsequent pregnancies, and gait asymmetry. Walking data were collected from an individual during 2 consecutive pregnancies during the second and third trimesters and 6 months postpartum of her first pregnancy and the first, second, and third trimesters and 6 months postpartum of her second pregnancy. Existing asymmetries in step length, anterior–posterior (AP) impulses, AP peak ground reaction forces, lateral impulses, and joint work systematically increased as her pregnancy progressed. These changes in asymmetry may be attributed to pelvic asymmetry, leading to asymmetric hip flexor and extensor length, or due to asymmetric plantar flexor strength, as suggested by her ankle work asymmetry. Relative to her first pregnancy, she had greater asymmetry in step length, step width, braking AP impulse, propulsive AP impulse, and peak braking AP ground reaction force during her second pregnancy, which may have resulted from increased joint laxity.

Keywords: walking, falls, balance control, load carriage

Females are at an increased risk of falling during pregnancy, with 27% experiencing a fall at least once.[1] Approximately 40% of all trauma-related visits to the emergency room or hospital admissions of pregnant women are attributed to accidental falls.[2–4] A number of anatomical and hormonal changes occur during pregnancy, which result in altered body mass, center-of-mass location, joint and ligament laxity, and musculotendon strength. These changes can lead to alterations in gait patterns and, ultimately, reduced balance control, leading to falls.

Gait kinetics have been extensively explored during pregnancy. Although joint demands are greater during pregnancy, pregnant women typically demonstrate reduced contributions from the hip and increased contributions from the ankle to total negative stance phase work generated by lower extremities in the sagittal plane during their second trimester.[5] Furthermore, pregnant women demonstrate greater ankle work and total lower-extremity work during stance relative to nonpregnant controls.[5] Some have found that the peak vertical ground reaction forces (GRFs) are reduced during pregnancy,[6] whereas others have reported that GRFs remain unchanged.[7] Spatiotemporal characteristics are also altered during pregnancy, wherein pregnant women typically display a shortened step length, increased step width, decreased cadence, and increased time spent in double-support phase.[8]

Gait asymmetry using these kinetic and spatiotemporal measures has been extensively studied in healthy individuals as well as in populations with increased fall risk, such as individuals post-stroke, those with lower-limb amputations, or in older adults.[9–12] Although most healthy individuals have some degree of gait asymmetry, severe asymmetry is a predictor of decreased balance control and fall risk.[9–11] However, changes in asymmetry during pregnancy are not well understood, and many of these symmetry measures have not been investigated throughout pregnancy. Most pregnant women experience some degree of pelvic asymmetry, which has been measured by the difference in the degree of pelvic anteversion between the right and left sides.[13] In addition, some women experience asymmetric laxity of the sacroiliac joints,[14] which may contribute to gait asymmetries and/or reduction in balance control. One study reported increased asymmetry in the hip flexion moments during the third trimester relative to nonpregnant individuals.[15] Others investigated trunk motion asymmetry in pregnant women with lumbopelvic pain and found that those with pain typically experienced greater rotational and translational asymmetry but did not include data on whether that asymmetry increased as pregnancy progressed.[16] Furthermore, women typically experience greater pain and joint laxity during their second pregnancy.[17] However, few studies have investigated whether gait asymmetry increases following subsequent pregnancies.

The increasing anterior load as well as changes in hormone production during pregnancy may exacerbate existing musculoskeletal imbalances, thus amplifying asymmetries that are present in most healthy nonpregnant individuals. Relaxin and progesterone levels are increased during pregnancy and cause weakened abdominal muscles, as does overstretching of the muscles due to increased abdominal size.[18,19] Increased sacroiliac joint laxity during pregnancy can lead to an increase in anterior pelvic tilt,[18] which results in shortened hip flexors, lengthened hamstrings, and increased lordosis of the spine.[20–22] As most women experience some asymmetry in their pelvic tilt,[13] this may lead to imbalances in hip flexor/extensor muscle length and strength.

The purpose of this study was to explore the effect of pregnancy progression and subsequent pregnancies on gait asymmetry, including differences in spatiotemporal and GRF variables. Joint work was analyzed to help interpret observed differences. We

Lefranc https://orcid.org/0000-0003-1071-9548
Klute https://orcid.org/0000-0001-9527-9590
Neptune (rneptune@mail.utexas.edu) is corresponding author, https://orcid.org/0000-0003-2425-004X

expected that the participant would experience greater asymmetry during pregnancy and that the degree of asymmetry would increase as the pregnancy progressed. In addition, we expected that the degree of asymmetry would be greater during a subsequent pregnancy relative to the first.

Methods

Data Collection

Kinematic and kinetic data were collected from one healthy woman (initially 1.65 m, 25 y) during 2 consecutive pregnancies that began ~138 weeks apart. Data were collected during the second trimester (2T, 20 wk, 62.3 kg), third trimester (3T, 34 wk, 69.3 kg), and 6 months postpartum (PP1, 61.2 kg) of her first pregnancy and during her first trimester (1T, 11 wk, 62.0 kg), early and late second trimester (2T-early, 19 wk, 63.3 kg; 2T-late, 25 wk, 65.9 kg), early and late third trimester (3T-early, 31 wk, 68.0 kg; 3T-late, 36 wk, 68.9 kg), and 6 months postpartum (PP2, 62.1 kg) of her second pregnancy. Although some biomechanical changes remain after pregnancy,[5,23,24] the postpartum data served as a reference point to identify potential trends that occurred during pregnancy, relative to before pregnancy, as data were not collected prior to both pregnancies. The participant provided written informed consent to participate in this study protocol approved by The University of Texas at Austin Institutional Review Board and explicitly consented to participating in a case study.

A 10-camera motion capture system (VICON) recorded full-body kinematic data at 120 Hz during steady-state treadmill walking. For the first pregnancy, a 42-marker modified Helen Hayes set was used to evaluate step width and length, whereas the same marker set with the addition of medial knee markers and 3 additional tracking markers on each thigh and shank segment (56 markers total) was used to also estimate joint work during the second pregnancy. Kinetic data were collected at 960 Hz from a split-belt instrumented treadmill (Motek). At each stage of pregnancy, the participant was asked to walk at a fixed ($1\ m{\cdot}s^{-1}$) speed and her self-selected (SS) overground speed, which was determined from the average of 3 trials of a 10-m walk test at her "comfortable, typical walking speed." Her SS speed was 1.30, 1.26, and 1.37 $m{\cdot}s^{-1}$ at 2T, 3T, and PP1 of her first pregnancy, respectively, and 1.27, 1.35, 1.3, 1.28, 1.18, and 1.36 $m{\cdot}s^{-1}$ at 1T, 2T-early, 2T-late, 3T-early, 3T-late, and PP2 of her second pregnancy, respectively. She reported being active throughout both pregnancies, and her activity levels remained consistent between the first and second pregnancies. Furthermore, she reported being right-leg dominant.

Data Analysis

Marker and GRF data were low-pass filtered at 6 Hz for the first pregnancy and at 6 Hz and 12 Hz, respectively, for the second pregnancy. Crossover steps were identified and removed from kinetic analyses. Twenty-four successful gait cycles were analyzed from each data collection. Motion data were processed and analyzed in Visual3D (C-Motion) and custom scripts in MATLAB (MathWorks) to calculate and aggregate study metrics and results. Several measures of gait asymmetry were evaluated by comparing step length, step width, temporal measures, and GRF patterns and impulses, which were selected because they are established measures of gait asymmetry in healthy and clinical populations.[9,10,25–27]

Step length was defined as the distance between the heel contact point of one foot to that of the contralateral foot, and step width was defined as the lateral distance between the center of mass and heel contact point at the instant of heel strike. Temporal asymmetry was evaluated using total step time, which was defined as the time between 2 consecutive heel strikes.

The GRF variables of interest were defined by the local and absolute extrema of each force pattern.[26] $F_{max,1}$ and $F_{max,2}$ were defined as the first and second local maximums of the vertical and mediolateral (ML) GRFs, respectively. F_{max} was defined as the absolute maximum of anterior–posterior (AP) GRFs, and F_{min} was defined as the local minimum of vertical GRF and absolute minimum of ML and AP GRFs. GRF impulse variables were calculated as the time integral of stance-phase GRFs, which were normalized by body weight and included the positive and negative portions of these integrals. $I_{AP(+)}$ and $I_{AP(-)}$ were defined as the positive and negative impulses for the AP GRF, respectively. $I_{ML(+)}$ and $I_{ML(-)}$ were defined as the positive and negative impulses for the ML GRF, respectively.

Positive and negative sagittal plane joint work of the hip, knee, and ankle joint were calculated within multiple regions of the stance phase for only the second pregnancy due to marker set limitations of the first pregnancy. The stance phase was divided into early stance, mid stance, terminal stance, and preswing. Early stance was defined as the initial double-support phase for a given foot, mid stance was defined as the first half of single-support phase and terminal stance was defined as the second half, and preswing was defined as the terminal double-support phase. Joint work asymmetry was determined for the joint work sign that is predominantly found in specific periods of stance. For example, the ankle generates positive work during the preswing phase, and thus, asymmetry of the positive ankle work was calculated for that period of stance.

A symmetry index (SI) was used to quantify asymmetries between right and left leg for the spatiotemporal and GRF variables as:

$$\mathrm{SI} = \frac{X_R - X_L}{0.5 \times (X_R + X_L)} \times 100\%, \tag{1}$$

where X_R is the variable for the right step and X_L is the variable for the subsequent left step.[25] An SI of 0% corresponds to perfect symmetry, whereas a positive (negative) SI corresponds to right (left) side dominance for a particular variable. SI was determined between successive gait cycles and then averaged across all gait cycles (n = 24 per data collection). Reported results primarily focused on qualitative trends in asymmetries across both pregnancies.

Results

At PP1 and PP2, the participant had a slightly longer left than right step length (Figure 1). Her step-length asymmetry for both walking speeds (SS and $1\ m{\cdot}s^{-1}$) generally increased as pregnancy progressed, except for the first pregnancy $1\ m{\cdot}s^{-1}$ condition, wherein asymmetry peaked during the second trimester. Step-length asymmetry was greater during the second pregnancy relative to the first, especially during SS walking. In addition, peak step-length asymmetry was greater when walking at $1\ m{\cdot}s^{-1}$ than during SS walking.

The participant displayed a slightly larger left than right step width for both pregnancies (see Appendix). There were no consistent changes in step-width asymmetry as pregnancy progressed for both walking speeds. The degree of step-width asymmetry was

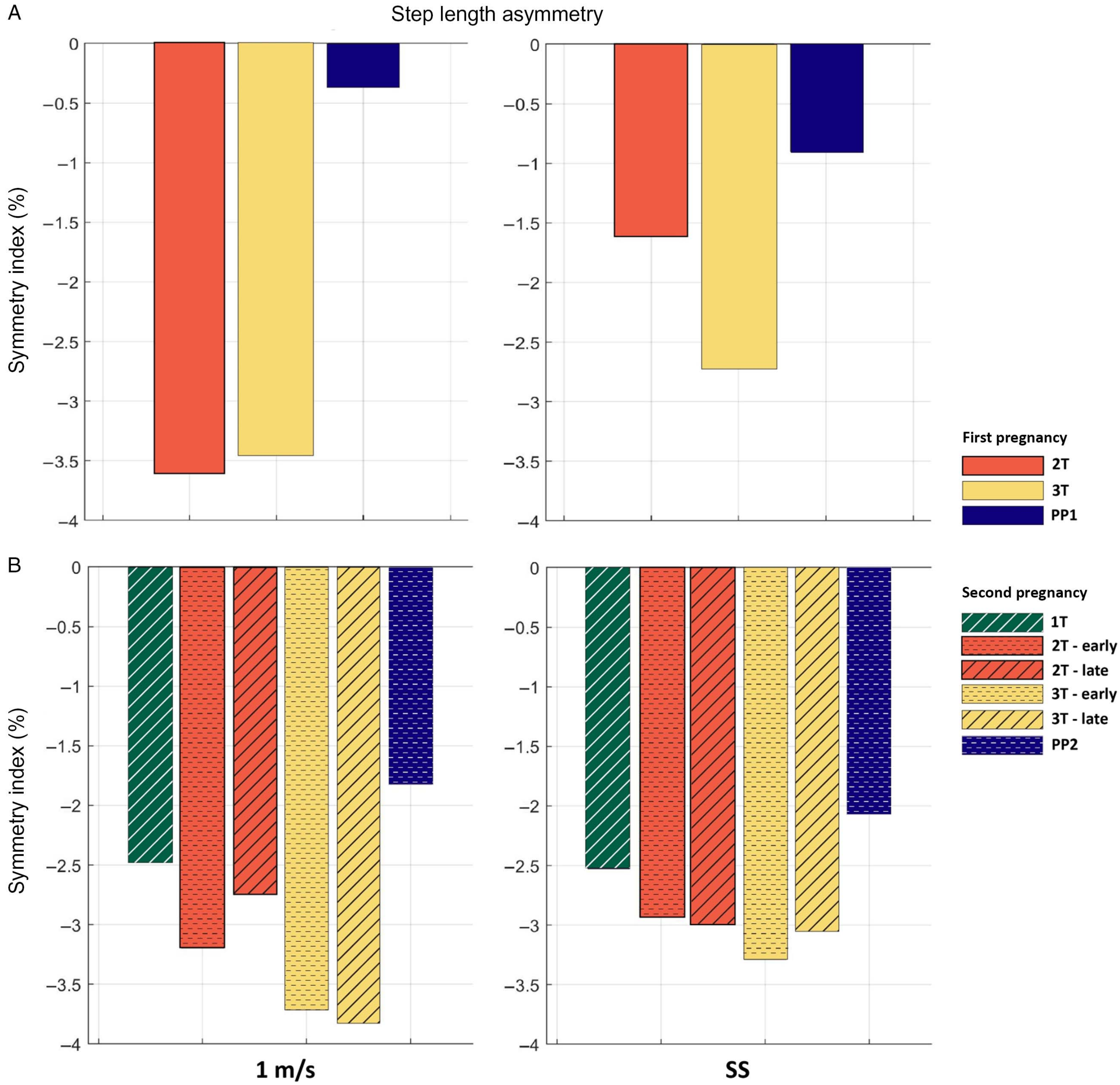

Figure 1 — Mean step length symmetry index values for the participant's first (left) and second (right) pregnancy when walking at 1 m·s^{-1} (A) and at SS speed (B). Negative symmetry index corresponds to longer left step length than right step length. PP1 indicates 6 months postpartum of her first pregnancy; PP2, 6 months postpartum of her second pregnancy; SS, self-selected; T1, first trimester; T2, second trimester; T3, third trimester.

greater during her second pregnancy relative to her first for the SS condition. However, the degree of asymmetry for the 1 m·s^{-1} condition of the first and second pregnancies was similar.

The participant displayed a slightly negative temporal SI, indicating that her left step took longer, on average, to complete than her right step (see Appendix). There were no consistent changes in temporal asymmetry as pregnancy progressed for both walking speeds, nor did it change from the first pregnancy to the second.

The vertical GRF remained relatively symmetric throughout both the first and second pregnancies (Figure 2). At PP1 and PP2, the participant displayed asymmetry for the peak propulsive (F_{max}, AP) and peak braking (F_{min}, AP) GRFs, and these asymmetries were greater during the second and third trimesters relative to postpartum. The participant also exhibited asymmetry for the peak lateral (F_{min}, ML), first medial peak ($F_{max,1}$, ML), and second medial peak ($F_{max,2}$, ML) GRFs. The peak lateral and first medial peak GRF asymmetries were greatest during the third trimester but

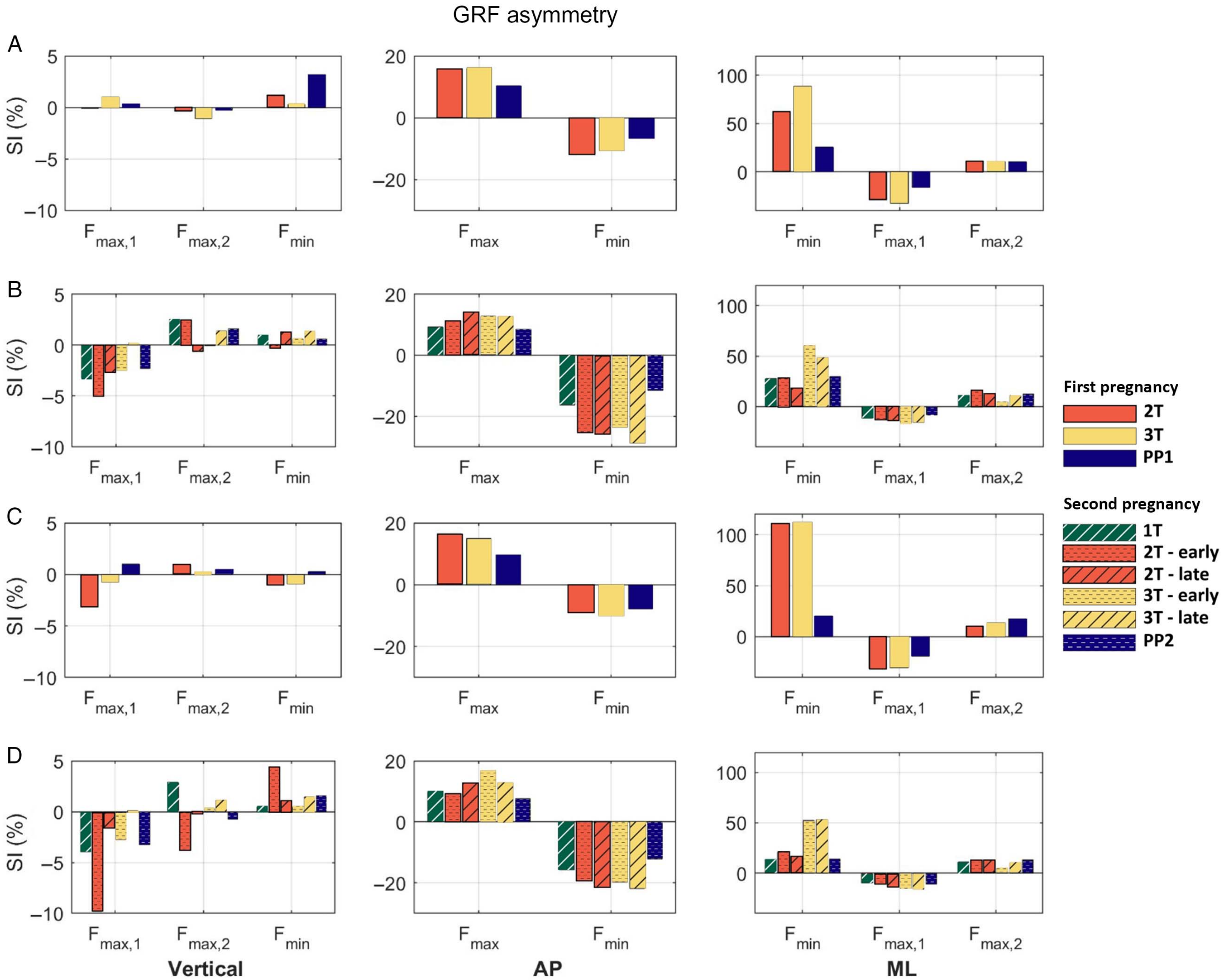

Figure 2 — (A) Mean GRF SI values for the participant's first pregnancy when walking at 1 m·s^{-1}. (B) Mean GRF SI values for the participant's second pregnancy when walking at 1 m·s^{-1}. (C) Mean GRF SI values for the participant's first pregnancy when walking at self-selected speed. (D) Mean GRF SI values for the participant's second pregnancy when walking at self-selected speed. Positive SI corresponds to right-leg dominance, and negative SI corresponds to left-leg dominance. AP indicates anterior–posterior; GRF, ground reaction force; ML, medial–lateral; PP1, 6 months postpartum of her first pregnancy; PP2, 6 months postpartum of her second pregnancy; SI, symmetry index; T1, first trimester; T2, second trimester; T3, third trimester.

did not always increase systematically across time points. Negative (braking) AP loading asymmetry was greater during the second pregnancy relative to the first, whereas ML loading asymmetry was greater during the first pregnancy. Also of note is that the magnitudes of the AP and ML GRF asymmetries (10%–110%) were substantially larger than the vertical GRF (<10%).

No trends in asymmetry were observed in the vertical GRF impulses (I_{vert}) or the positive (medial) ML impulses ($I_{ML(+)}$) (Figure 3). At PP1 and PP2, the participant displayed slight left-leg dominance for the positive AP impulses ($I_{AP(+)}$) and slight right-leg dominance for the negative AP impulses ($I_{AP(-)}$) for both the first and second pregnancies. The positive AP impulse became more asymmetric during pregnancy relative to PP1 and PP2 at both walking speeds (SS and 1 m·s^{-1}). However, the participant exhibited greater AP impulse asymmetry at 2T relative to 3T for the first pregnancy. The AP impulse asymmetry was greater during the second pregnancy relative to the first. At PP1 and PP2, the participant displayed right-leg dominance for the negative (lateral) ML impulses ($I_{ML(-)}$). This asymmetry became more apparent during 2T and 3T at both walking speeds. The negative (lateral) ML impulse was greater during the first pregnancy relative to the second.

At PP2, the participant generated more negative work during early stance with her left ankle for both walking speeds (Figure 4). Furthermore, she generated more positive work during preswing with her right ankle. These ankle asymmetries systematically became more pronounced as the second pregnancy progressed. During early stance, she demonstrated right foot dominance in the negative work generated by her knee for the 1 m·s^{-1} condition, which became more apparent as pregnancy progressed (Figure 5). She also generated more positive work with her right knee during

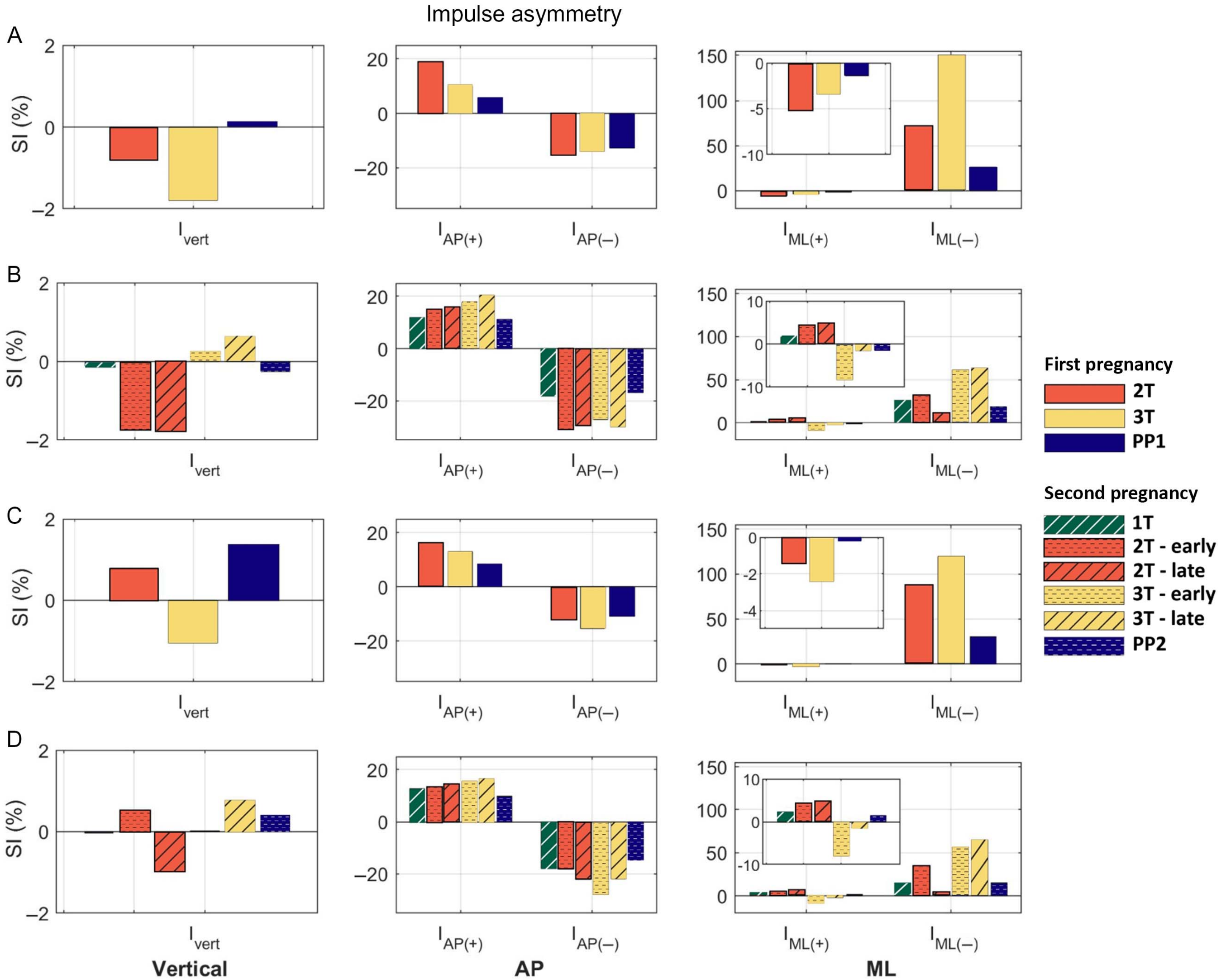

Figure 3 — (A) Mean GRF impulse SI values for the participant's first pregnancy when walking at 1 m·s^{-1}. (B) Mean GRF impulse SI values for the participant's second pregnancy when walking at 1 m·s^{-1}. (C) Mean GRF impulse SI values for the participant's first pregnancy when walking at self-selected speed. (D) Mean GRF impulse SI values for the participant's second pregnancy when walking at self-selected speed. Positive SI corresponds to right-leg dominance, and negative SI corresponds to left-leg dominance. Positive ML GRF impulse SI values are shown enlarged above the original plot. AP indicates anterior–posterior; GRF, ground reaction force; ML, medial–lateral; PP1, 6 months postpartum of her first pregnancy; PP2, 6 months postpartum of her second pregnancy; SI, symmetry index; T1, first trimester; T2, second trimester; T3, third trimester.

terminal stance. During early stance, her right hip generated more positive work than her left; however, this asymmetry became less apparent as pregnancy progressed (Figure 6). During mid and terminal stance, her left hip generated more negative work than the right. Her right hip produced more positive work during preswing than her left, which became more pronounced as her pregnancy progressed.

Discussion

We expected that gait asymmetry would increase during pregnancy relative to postpartum and that the degree of asymmetry would increase as pregnancy progressed. Consistent with our expectation, we found that existing asymmetries in step length, AP impulses (second pregnancy only), AP peak GRFs, and negative ML impulses systematically increased as pregnancy progressed. However, the negative (lateral) ML impulse is a relatively small component of the total ML impulse, and thus, this measure is sensitive to relatively small differences between the right and left legs. Although the negative (lateral) ML peak GRFs and first peak positive (medial) ML GRFs were noticeably larger at 3T relative to postpartum, asymmetry did not increase systemically across each stage of pregnancy.

At PP1 and PP2, the participant had a slightly longer left than right step length, which likely resulted from plantar flexor asymmetry. She also demonstrated right foot dominance for her positive AP (propulsive) impulse while demonstrating left foot dominance for her negative AP (braking) impulse. These results suggest that

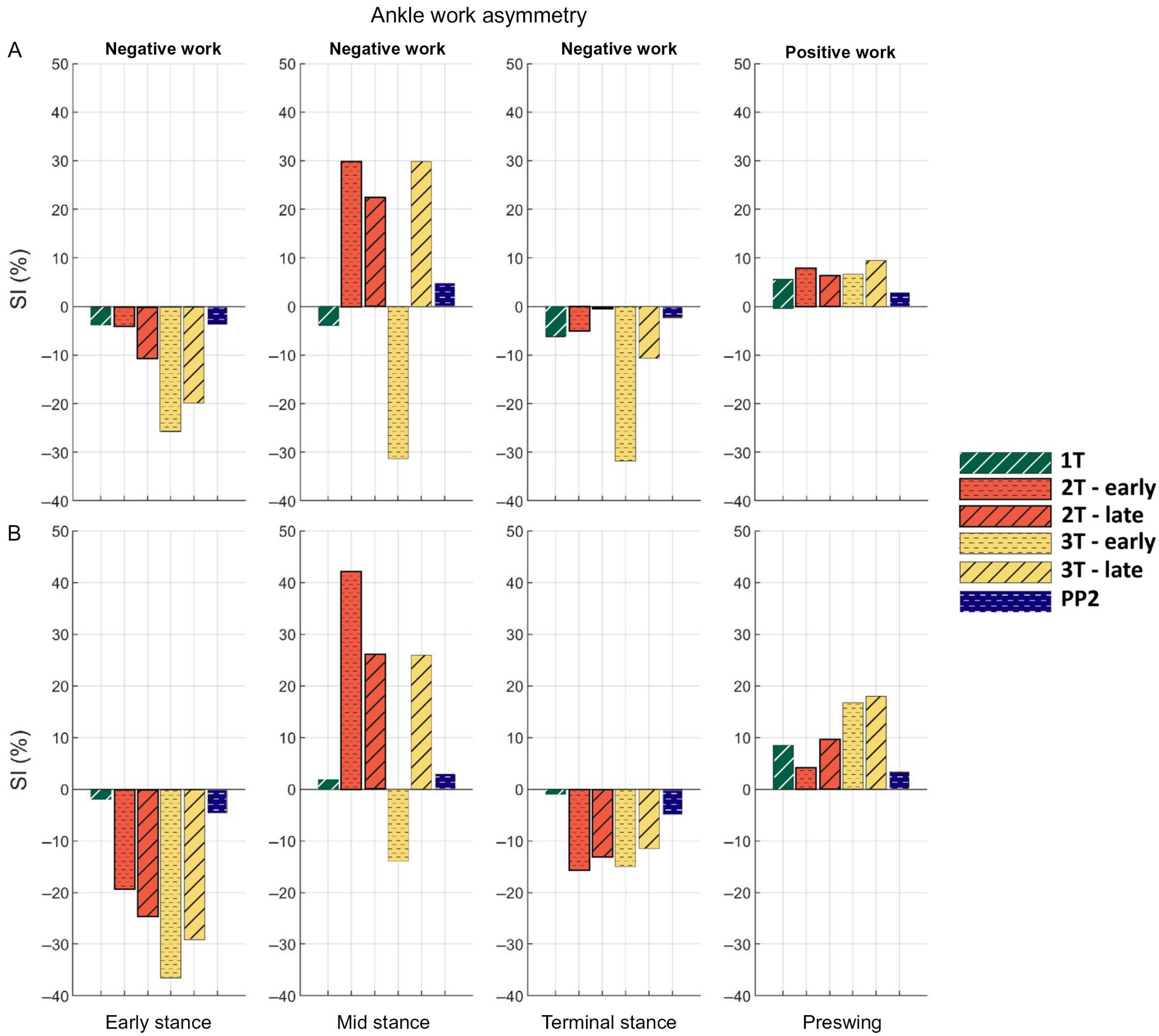

Figure 4 — Mean joint work SI values for the ankle joint for second pregnancy when the participant was walking at 1 m·s^{-1} (A) and at self-selected walking speed (B). Each column corresponds to a different region of the stance phase. SI was only determined for the predominant joint work sign for each region of stance. Positive SI corresponds to right-leg dominance, and negative SI corresponds to left-leg dominance. PP2 indicates 6 months postpartum of her second pregnancy; SI, symmetry index; T1, first trimester; T2, second trimester; T3, third trimester.

there is an inverse relationship between propulsive impulse and step-length asymmetry, which is consistent with previous work analyzing individuals poststroke.[27]

During preswing, the participant demonstrated greater work generation by her right ankle relative to her left, which became more apparent as pregnancy progressed. These results suggest that asymmetries in concentric ankle plantar flexor strength and/or activation during push-off contribute to asymmetric propulsion. Furthermore, she displayed increased negative work generated by her left ankle plantar flexors relative to her right during early stance, which also became more apparent as pregnancy progressed, resulting in a larger braking impulse by the left leg. These findings are consistent with previous work that identified the plantar flexors as primary contributors to braking and forward propulsion[28,29].

Given that the vasti and gluteus maximus are also contributors to the negative AP GRFs,[29] we would also expect the negative and positive power generated by her knee and hip joints, respectively, to exhibit left foot dominance during early stance. Conversely, she demonstrated increased early stance knee and hip work by her right leg relative to her left. This suggests that her plantar flexors are the primary contributors to the asymmetric braking rather than the hip and knee extensors. Furthermore, increased work generated by the hip and knee of the right leg during early stance suggests a compensatory mechanism by the right knee and hip extensors to

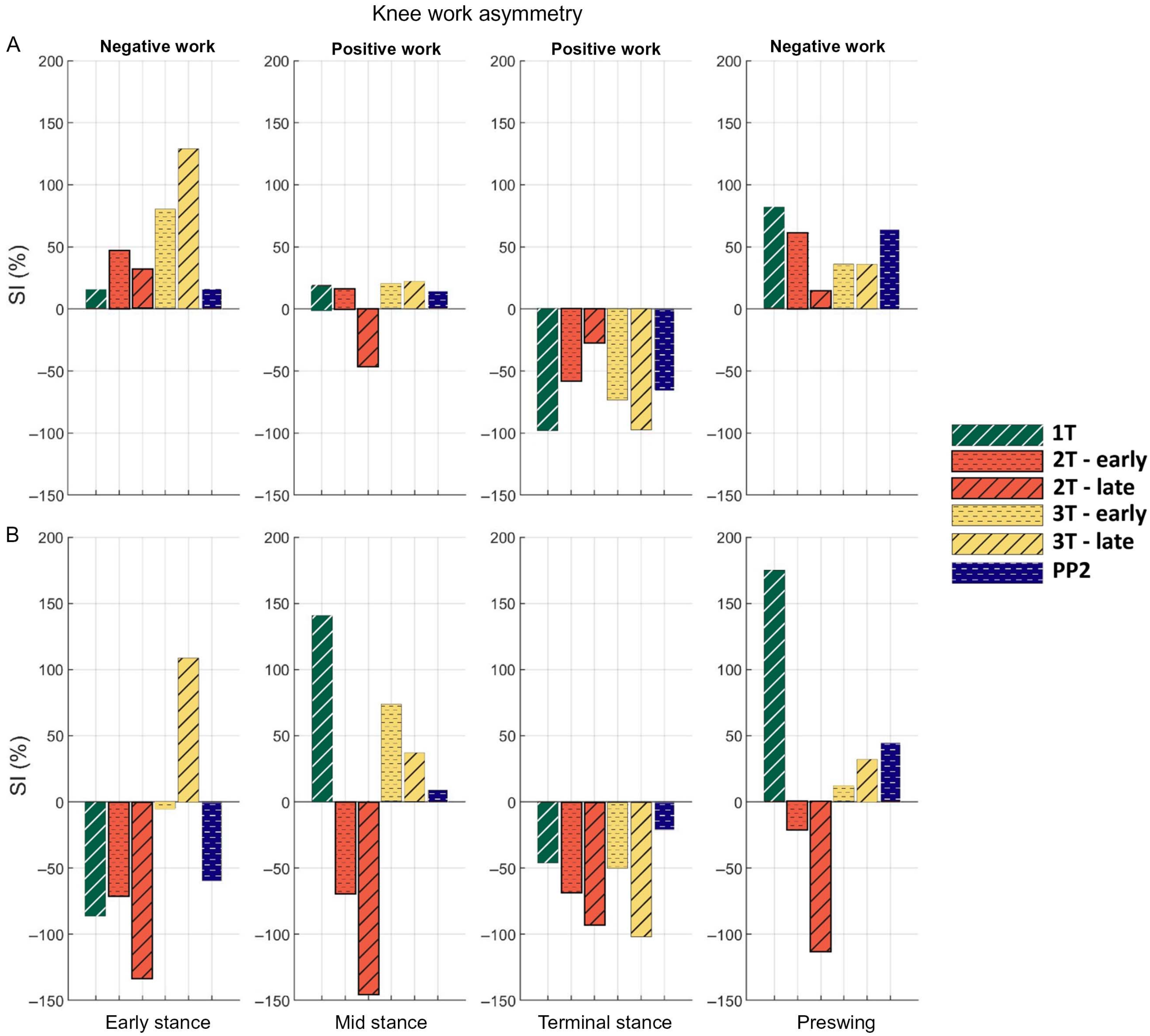

Figure 5 — Mean joint work SI values for the knee joint for second pregnancy when the participant was walking at 1 m·s^{-1} (A) and at self-selected walking speed (B). Each column corresponds to a different region of the stance phase. SI was only determined for the predominant joint work sign for each region of stance. Positive SI corresponds to right-leg dominance, and negative SI corresponds to left-leg dominance. PP2 indicates 6 months postpartum of her second pregnancy; SI, symmetry index; T1, first trimester; T2, second trimester; T3, third trimester.

regain symmetry by counteracting the braking impulse generated by the left plantar flexors. During preswing, she also demonstrated greater positive hip flexor power generated by her right leg, which systematically increased as pregnancy progressed (Figure 6). As the iliopsoas contributes to leg swing initiation during preswing,[30] this suggests that hip flexor asymmetry may have been a compensatory mechanism to minimize the step-length asymmetry. Conversely, hip flexor asymmetry observed during pregnancy may also result from pelvic tilt asymmetry exacerbated by the hormones released during pregnancy, which may cause asymmetric hip flexor length and strength.[13,18,20–22]

Although the participant demonstrated some step-width and temporal asymmetry at postpartum, in contrast to our expectation, we did not observe any systematic increases in these asymmetries as pregnancy progressed. Thus, the increase in the AP impulse asymmetry as pregnancy progressed was due primarily to an increase in GRF magnitude rather than changes in temporal asymmetries. The participant exhibited wider left than right step width (see Appendix), which was consistent with shifting the center of mass closer to her dominant (right) foot.

We expected that the participant would exhibit greater gait asymmetry during the second pregnancy relative to the first. In

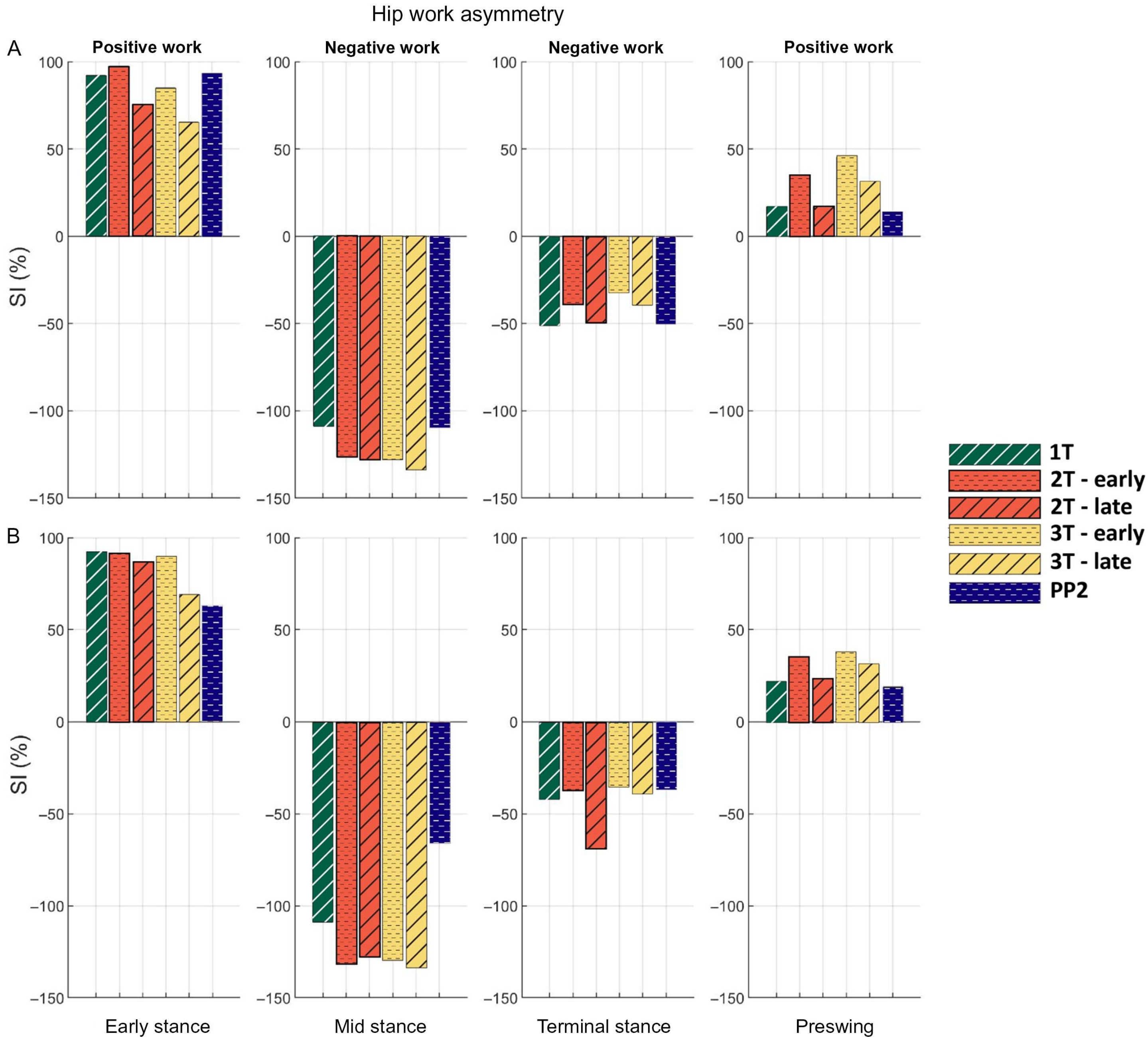

Figure 6 — Mean joint work SI values for the hip joint for second pregnancy when the participant was walking at 1 m·s^{-1} (A) and at self-selected walking speed (B). Each column corresponds to a different region of the stance phase. SI was only determined for the predominant joint work sign for each region of stance. Positive SI corresponds to right-leg dominance, and negative SI corresponds to left-leg dominance. PP2 indicates 6 months postpartum of her second pregnancy; SI, symmetry index; T1, first trimester; T2, second trimester; T3, third trimester.

agreement with our expectation, she displayed greater asymmetry of her step length, step width (for the SS condition), negative and positive AP impulse, and peak negative AP GRF. During her final data collection of each pregnancy (3T/3T-late for the first/second pregnancy), her step-length asymmetry was 11% larger at SS and 9% larger while walking 1 m·s^{-1} for the second pregnancy relative to the first. Her positive AP impulse asymmetry increased by 25% and 98% at SS and 1 m·s^{-1}, respectively, whereas her negative AP impulse asymmetry increased by 41% and 115% at SS and 1 m·s^{-1}, respectively. The magnitude of her peak negative AP GRF asymmetry increased by 126% and 208% for her second pregnancy relative to the first while walking at SS and 1 m·s^{-1}, respectively. These results suggest that walking at a nonpreferred walking speed might exacerbate existing asymmetries in braking and propulsion.

The changes to the body and hormones present during pregnancy can cause permanent anatomical and biomechanical changes postpartum, such as further increased joint laxity,[23,31] altered foot anthropometry and mechanics,[24] and internal tibial rotation.[32] Thus, it is likely that multiple pregnancies may cause an additive effect of these biomechanical changes, which may contribute to increased asymmetries in step length and the AP GRFs. Furthermore, women commonly experience greater joint laxity during their second pregnancy relative to their first,[17] which may cause pelvic tilt asymmetry that is present in the first pregnancy to become more apparent in subsequent pregnancies.

In addition, women typically experience greater back pain during their second pregnancy, relative to their first,[17] and pregnancy-related pain is typically correlated with increased kinematic asymmetry and asymmetric laxity of the sacroiliac joints.[14,16] However, future studies are needed to determine whether there is a direct relationship between the increase in asymmetry and the increase in pain observed in subsequent pregnancies. Additional research is also needed to investigate whether increased asymmetry during subsequent pregnancies also corresponds to increased fall risk.

A limitation of this study was that no data were collected prior to both pregnancies, and first pregnancy data were not collected until the second trimester; thus, there was no baseline for both pregnancies. Although postpartum data served to identify any trends that occurred during pregnancy relative to before pregnancy, biomechanical changes occurring during pregnancy may still be present in the postpartum data. Studies have found that the altered gait biomechanics that emerge during pregnancy can linger several months postpartum.[5] However, the extent to which those changes affect balance control during walking relative to nulliparous individuals is unclear.

Another limitation of this study was the potential influence of day-to-day loading on inducing or prolonging asymmetry after the first pregnancy. The participant reported that between pregnancies, she had a slight preference to carry her first child in her left arm so that she could complete tasks with her right (dominant) hand. She also reported that by the time her second pregnancy began, her first child was too heavy to comfortably carry with one arm, but it is likely that the child was still held asymmetrically. Thus, it is possible that carrying her child may have induced additional asymmetry between pregnancies or during the second pregnancy.

This study did not separate the observed pregnancy-related changes from potential age-related changes or multiple testing-related changes. However, as the study took place over the course of 2 and half years and involved a young, healthy individual, we assumed age-related changes to be negligible. The subject maintained similar body mass and SS walking speed during the second and third trimesters of the second pregnancy relative to the first, and the same equipment was used to collect data throughout both pregnancies.

This case study provides a brief examination of asymmetry in pregnancy. As data were only collected from one individual, the results are not generalizable for all pregnant individuals. Further study with more participants is needed to fully understand the relationships between these asymmetry measures, dynamic balance, and pregnancy. A final limitation is that we used a split-belt treadmill that may have influenced the participant's step width. However, it is unclear whether it would affect step width asymmetry.

This case study analyzed an individual across 2 consecutive pregnancies and found that AP and lateral GRF impulse, AP peak GRF, and step-length asymmetries increased as pregnancy progressed. In addition, the degree of the AP and step-length asymmetry increased in her subsequent pregnancy. Slight step-width and temporal asymmetries were present at baseline; however, the degree of this asymmetry did not change as pregnancy progressed or from one pregnancy to the next. Step-length and GRF asymmetries in the AP direction can be attributed to increased imbalances in the plantar flexor muscles. The hip flexor and extensor and knee extensor asymmetries likely resulted as compensatory strategies to counteract asymmetries generated by the plantar flexors.

Acknowledgments

This study was supported in part by Department of Veterans Affairs awards RX003138 and RX002974. The authors would also like to thank the study participant and members of the Neuromuscular Biomechanics Lab who helped with the data collection.

References

1. Dunning K, LeMasters G, Levin L, Bhattacharya A, Alterman T, Lordo K. Falls in workers during pregnancy: risk factors, job hazards, and high risk occupations. *Am J Ind Med*. 2003;44(6):664–672. PubMed ID: 14635243 doi:10.1002/ajim.10318
2. Connolly AM, Katz VL, Bash KL, McMahon MJ, Hansen WF. Trauma and pregnancy. *Am J Perinatol*. 1997;14(6):331–336. PubMed ID: 9217953 doi:10.1055/s-2007-994155
3. Neufeld JDG, Moore EE, Marx JA, Rosen P. Trauma in pregnancy. *Emerg Med Clin North Am*. 1987;5(3):623–640. PubMed ID: 3308431 doi:10.1016/S0733-8627(20)31063-4
4. Weiss HB. Pregnancy-associated injury hospitalizations in Pennsylvania, 1995. *Ann Emerg Med*. 1999;34(5):626–636. PubMed ID: 10533011 doi:10.1016/S0196-0644(99)70165-4
5. Bagwell JJ, Reynolds N, Walaszek M, et al. Lower extremity kinetics and muscle activation during gait are significantly different during and after pregnancy compared to nulliparous females. *Gait Posture*. 2020;81:33–40. PubMed ID: 32659459 doi:10.1016/j.gaitpost.2020.07.002
6. Branco M, Santos-Rocha R, Aguiar L, Vieira F, Veloso A. Kinematic analysis of gait in the second and third trimesters of pregnancy. *J Pregnancy*. 2013;2013:1–9. doi:10.1155/2013/718095
7. McCrory JL, Chambers AJ, Daftary A, Redfern MS. Ground reaction forces during gait in pregnant fallers and non-fallers. *Gait Posture*. 2011;34(4):524–528. PubMed ID: 21820902 doi:10.1016/j.gaitpost.2011.07.007
8. Błaszczyk JW, Opala-Berdzik A, Plewa M. Adaptive changes in spatiotemporal gait characteristics in women during pregnancy. *Gait Posture*. 2016;43:160–164. PubMed ID: 26480840 doi:10.1016/j.gaitpost.2015.09.016
9. Yogev G, Plotnik M, Peretz C, Giladi N, Hausdorff JM. Gait asymmetry in patients with Parkinson's disease and elderly fallers: when does the bilateral coordination of gait require attention? *Exp Brain Res*. 2007;177(3):336–346. PubMed ID: 16972073 doi:10.1007/s00221-006-0676-3
10. Bautmans I, Jansen B, van Keymolen B, Mets T. Reliability and clinical correlates of 3D-accelerometry based gait analysis outcomes according to age and fall-risk. *Gait Posture*. 2011;33(3):366–372. PubMed ID: 21227697 doi:10.1016/j.gaitpost.2010.12.003
11. Gillain S, Boutaayamou M, Schwartz C, et al. Gait symmetry in the dual task condition as a predictor of future falls among independent older adults: a 2-year longitudinal study. *Aging Clin Exp Res*. 2019;31(8): 1057–1067. PubMed ID: 31069697 doi:10.1007/s40520-019-01210-w
12. Nolan L, Wit A, Dudziñski K, Lees A, Lake M, Wychowañski M. Adjustments in gait symmetry with walking speed in trans-femoral and trans-tibial amputees. *Gait Posture*. 2003;17(2):142–151. PubMed ID: 12633775 doi:10.1016/S0966-6362(02)00066-8
13. Franklin ME, Conner-Kerr T. An analysis of posture and back pain in the first and third trimesters of pregnancy. *J Orthop Sports Phys Ther*. 1998; 28(3):133–138. PubMed ID: 9742469 doi:10.2519/jospt.1998.28.3.133
14. Damen L, Buyruk HM, Güler-Uysal F, Lotgering FK, Snijders CJ, Stam HJ. Pelvic pain during pregnancy is associated with asymmetric laxity of the sacroiliac joints. *Acta Obstet Gynecol Scand*. 2001; 80(11):1019–1024. PubMed ID: 11703199 doi:10.1034/j.1600-0412.2001.801109.x

15. Branco M, Santos-Rocha R, Vieira F, Aguiar L, Veloso AP. Three-dimensional kinetic adaptations of gait throughout pregnancy and postpartum. *Scientifica*. 2015;2015:1–14. doi:10.1155/2015/580374
16. Tanigawa A, Morino S, Aoyama T, Takahashi M. Gait analysis of pregnant patients with lumbopelvic pain using inertial sensor. *Gait Posture*. 2018;65:176–181. PubMed ID: 30558927 doi:10.1016/j.gaitpost.2018.07.165
17. Lindgren A, Kristiansson P. Finger joint laxity, number of previous pregnancies and pregnancy induced back pain in a cohort study. *BMC Pregnancy Childbirth*. 2014;14(1):61. doi:10.1186/1471-2393-14-61
18. Gilleard WL, Brown JM. Structure and function of the abdominal muscles in primigravid subjects during pregnancy and the immediate postbirth period. *Phys Ther*. 1996;76(7):750–762. PubMed ID: 8677279 doi:10.1093/ptj/76.7.750
19. Hagen R. Pelvic girdle relaxation from an orthopaedic point of view. *Acta Orthop Scand*. 1974;45(4):550–563. PubMed ID: 4451061 doi:10.3109/17453677408989178
20. Levine D, Michael WW. The effects of pelvic movement on lumbar lordosis in the standing position. *J Orthop Sport Phys Ther*. 1996; 24(3):130–135. doi:10.2519/jospt.1996.24.3.130
21. López-Miñarro P, et al. Acute effects of hamstring stretching on sagittal spinal curvatures and pelvic tilt. *J Hum Kinet*. 2012;31(2012): 69–78. doi:10.2478/v10078-012-0007-7
22. Preece SJ, et al. Comparison of pelvic tilt before and after hip flexor stretching in healthy adults. *J Manip Physiol Ther*. 2021;44(4):289–294. PubMed ID: 29705172 doi:10.1016/j.jmpt.2020.09.006
23. Chu SR, Boyer EH, Beynnon B, Segal NA. Pregnancy results in lasting changes in knee joint laxity. *PM R*. 2019;11(2):117–124. PubMed ID: 29964215 doi:10.1016/j.pmrj.2018.06.012
24. Segal NA, Boyer ER, Teran-Yengle P, Glass NA, Hillstrom HJ, Yack HJ. Pregnancy leads to lasting changes in foot structure. *Am J Phys Med Rehabil*. 2013;92(3):232–240. PubMed ID: 23117270 doi:10.1097/PHM.0b013e31827443a9
25. Robinson RO, Herzog W, Nigg BM. Use of force platform variables to quantify the effects of chiropractic manipulation on gait symmetry. *J Manipulative Physiol Ther*. 1987;10(4):172–176. PubMed ID: 2958572
26. Herzog W, Nigg BM, Read LJ, Olsson E. Asymmetries in ground reaction force patterns in normal human gait. *Med Sci Sports Exerc*. 1989;21(1):110–114. PubMed ID: 2927295 doi:10.1249/00005768-198902000-00020
27. Balasubramanian CK, Bowden MG, Neptune RR, Kautz SA. Relationship between step length asymmetry and walking performance in subjects with chronic hemiparesis. *Arch Phys Med Rehabil*. 2007;88(1):43–49. PubMed ID: 17207674 doi:10.1016/j.apmr.2006.10.004
28. Neptune RR, Kautz SA, Zajac FE. Contributions of the individual ankle plantar flexors to support, forward progression and swing initiation during walking. *J Biomech*. 2001;34(11):1387–1398. PubMed ID: 11672713 doi:10.1016/s0021-9290(01)00105-1
29. Neptune RR, Zajac FE, Kautz SA. Muscle force redistributes segmental power for body progression during walking. *Gait Posture*. 2004;19(2):194–205. PubMed ID: 15013508 doi:10.1016/S0966-6362(03)00062-6
30. Neptune RR, Sasaki K, Kautz SA. The effect of walking speed on muscle function and mechanical energetics. *Gait Posture*. 2008; 28(1):135–143. PubMed ID: 18158246 doi:10.1016/j.gaitpost.2007.11.004
31. Schauberger CW, Rooney BL, Goldsmith L, Shenton D, Silva PD, Schaper A. Peripheral joint laxity increases in pregnancy but does not correlate with serum relaxin levels. *Am J Obstet Gynecol*. 1996; 174(2):667–671. PubMed ID: 8623804 doi:10.1016/S0002-9378(96)70447-7
32. Rabe KG, Segal NA, Waheed S, Anderson DD. The effect of arch drop on tibial rotation and tibiofemoral contact stress in postpartum women. *PM R*. 2018;10(11):1137–1144. PubMed ID: 29705172 doi:10.1016/j.pmrj.2018.04.006

Appendix

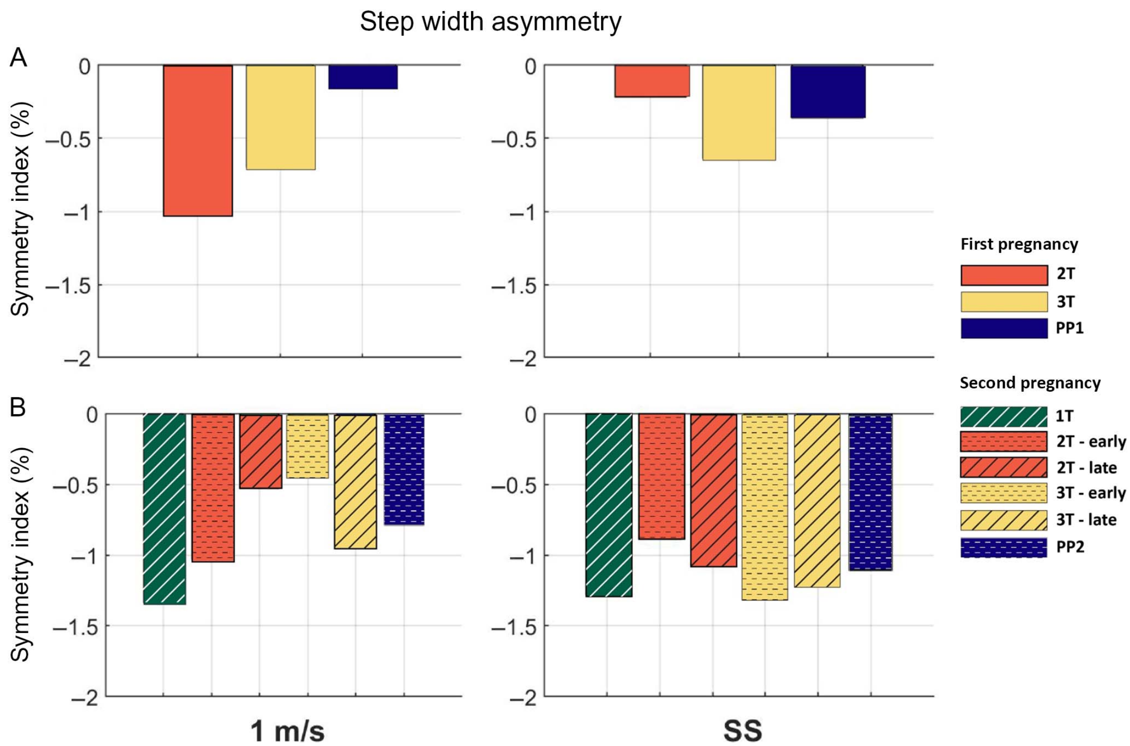

Figure A1 — Mean step width symmetry index values for the participant's first (A) and second (B) pregnancy when walking at 1 m·s^{-1} (left) and at SS speed (right). Negative symmetry index corresponds to wider left step width than right step width. PP1 indicates 6 months postpartum of her first pregnancy; PP2, 6 months postpartum of her second pregnancy; SS, self-selected; T1, first trimester; T2, second trimester; T3, third trimester.

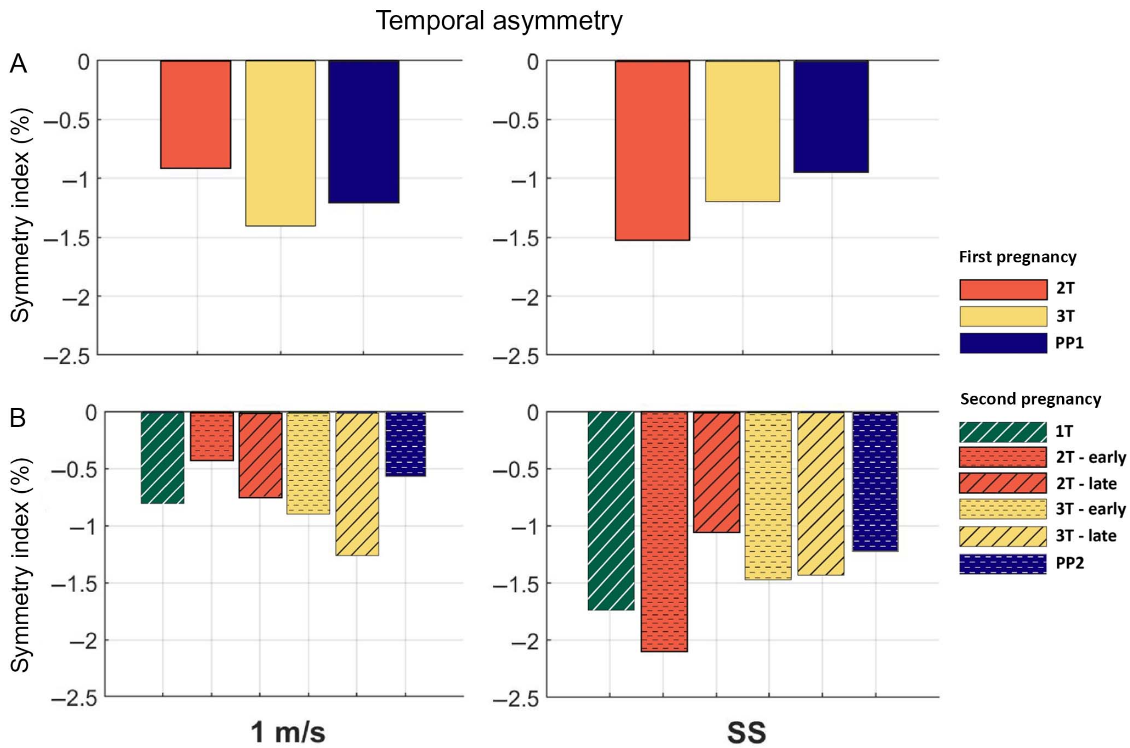

Figure A2 — Mean temporal symmetry index values for the participant's first (A) and second (B) pregnancy when walking at 1 m·s^{-1} (left) and at self-selected speed (right). Negative symmetry index corresponds to longer left step duration than right step duration. PP1 indicates 6 months postpartum of her first pregnancy; PP2, 6 months postpartum of her second pregnancy; SS, self-selected; T1, first trimester; T2, second trimester; T3, third trimester.