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The effects of total ankle arthroplasty on postural stability and loading symmetry in quiet stance

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ABSTRACT

Ankle osteoarthritis is a debilitating condition affecting about 1% of the population with approximately 50,000 new instances annually. One treatment is total ankle arthroplasty (TAA), however, its effects on balance are not well understood. This study analyzed balance over a two-year period following TAA. 408 subjects (177 left, 231 right ankles) diagnosed with end-stage ankle osteoarthritis performed quiet standing trials while center of pressure (COP) data were collected. Data were compared across three time points (pre-op, 1-year, and 2-years post-op) and between surgical and non-surgical limbs using a linear mixed model with significance set at $P = 0.05$. COP excursions in the feet-together condition were not significantly different between limbs after 2 years in anteroposterior or mediolateral directions ($P = 0.06$, 0.08) after being significantly different between limbs in the anteroposterior ($P = 0.014$) and mediolateral direction ($P < 0.001$) pre-op. The vertical ground reaction force significantly decreased across time in the non-surgical limb, while reciprocally increasing in the surgical limb ($P < 0.001$). After 2 years, no significant difference in vertical ground reaction force between limbs existed ($P = 0.20$). Limb asymmetry indices decreased at each time point in both conditions (all $P < 0.001$) and were not significantly different from zero after 2 years in the feet-together condition ($P = 0.290$). In conclusion, surgical limb balance improved compared to pre-op, resulting in increased symmetry between limbs after 2 years. Vertical ground reaction forces on both limbs converge and limb asymmetry indices approach zero two years post-op. Differences in the COP excursion-loading symmetry relationship between limbs could be useful for identifying instability in other pathologies.

1. Introduction

Ankle osteoarthritis (OA) is a debilitating condition that affects 1% of the global population with 50,000 new instances reported each year (Hintermann et al., 2002; Peyron, 1984). Patients with ankle OA can experience severe pain, muscle atrophy, limited ability to walk unassisted, and difficulty performing daily activities (Cook et al., 2010; Domsic and Saltzman, 1998). Beyond pain and functional limitations, weakness of the ankle puts patients at increased risk of injury from falls (Whipple et al., 1987).

Osteoarthritis is known to cause functional impairments, such as a decrease in postural stability, (Lord et al., 2000; Queen et al., 2013; Valderrabano et al., 2011; Whipple et al., 1987) which can increased the risk of falls, particularly in older adults (Lord et al., 2000; Queen et al., 2013; Richardson et al., 2014; Valderrabano et al., 2011; Whipple et al., 1987). Difficulty employing ankle-driven balance recovery strategies, due to increased muscle latency in response to perturbations and decreased postural stability resulting from OA, causes an increase in fall risk for older ankle OA patients (Lord et al., 2000). Furthermore, patients may load asymmetrically, possibly in order to relieve discomfort or because of structural deformities, which increases center of pressure (COP) excursions and has been shown to negatively affect postural stability (Genthon and Rougier, 2005). In populations with decreased or damaged ankle proprioception, such as patients with ankle prostheses, research has indicated that patients are more likely to experience greater pressures beneath the non-surgical limb and shift the COP of the surgical limb posteriorly and laterally when performing static balance tasks (Natsakis et al., 2015; Rougier and Bergeau, 2009). In combination, the data suggest that ankle OA patients may place greater loads on their unaffected limb, leading to increased COP excursion in the affected limb (Genthon and

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Rougier, 2005; Horisberger et al., 2009). Patients who have undergone total ankle arthroplasty (TAA) may also exhibit these tendencies of decreased postural stability, increased fall risk, and loading asymmetry as a result of proprioceptive changes that occur with surgery (Butler et al., 2015; Easley et al., 2011; Lord et al., 2000; Riemann and Guskiewicz, 2000).

Total ankle arthroplasty (TAA) is a surgical treatment for end-stage ankle OA that has been shown to benefit physical and psychological symptoms of ankle OA (Easley et al., 2011). Acute trauma or repeated injury to ankle joint structures can damage mechanoreceptors (Riemann and Guskiewicz, 2000). Further, surgical interventions to resolve ankle OA, including TAA, involve the resection of articular structures, areas dense with mechanoreceptors (Delahunt 2007; Riemann & Guskiewicz 2000). Therefore, patients who have undergone surgical treatment for ankle OA or have repeated trauma to the ankle joint may have a lack of positional sense of their ankle and delays in sensory signals from the ankle (Delahunt, 2007; Riemann and Guskiewicz, 2000). Neuromuscular feedback issues in ankle OA and TAA may be further exacerbated by the patients' tendency to asymmetrically load their limbs causing patients to sway noticeably, even in static conditions such as bilateral quiet stance.

One of the most common methods for measuring sway and postural stability is using center of pressure (COP)-related metrics (Li et al., 2016). In particular, mean COP velocity has been validated as a measure of postural instability (Sobanska et al., 2016). COP measures have often been used to measure postural stability performance in both healthy subjects (Li et al., 2016; Qiu and Xiong, 2015) and patient populations that are considered at increased risk for stability issues, such as Parkinson's disease (Błaszczyk et al., 2007) and post-concussion (Powers et al., 2014). Many of the metrics devised by Prieto et al. are used to describe success or failure of balance tasks (Prieto et al., 1996). However, in recent studies, non-linear measures are often used and it has been suggested that COP measures may be a better indicator of strategy than success or failure (Gladish et al., 2017; Powell and Williams III, 2015). In summary, COP measures are the most common metrics used to analyze postural stability, although the interpretation of those metrics is debated in the literature.

Existing research has identified a link between decreases in postural stability with fall risk, specifically in older adults (Lord et al., 2000). Though research exists on postural stability and loading asymmetry in ankle OA patients, it lacks COP-related measures and longitudinal data. Butler et al. (2015) found that only 9% of TAA patients passed a single-leg stance test one year after surgery, while hip and knee patients had 63% and 69% pass rates of the same balance test, respectively (Butler et al., 2015). Lee et al. (2010) demonstrated that TAA patients exhibited greater hip excursion, had greater difficulty controlling weight shift in the AP direction, and had a more asymmetrical loading pattern during quiet stance when compared to healthy controls (Lee et al., 2010). Despite these results, a paucity of literature exists reporting changes in COP-related balance measures in TAA patients across time-course of recovery from TAA. Therefore, the purpose of this study was to investigate the changes in postural stability as quantified by COP-based measures during recovery from TAA. It was hypothesized that COP excursion and COP mean velocity in the surgical limb would decrease at each successive time point, and that the load on each limb would converge to 50% body weight as recovery time increased.

2. Methods

Data from 408 subjects were analyzed. Data were included for patients if they had usable data for the pre-op visit and at least one post-op visit. The demographics for the subjects are listed in Table 3-1. All subjects had end-stage ankle arthritis (177 left and 231 right ankles) as diagnosed by an orthopedic surgeon and were scheduled for a total ankle arthroplasty within two weeks of initial testing (PRE). Subjects returned one (1YR) and two years (2YR) post-surgery to repeat the testing procedures. Participants were included in this study if they (1) were capable of independent ambulation without the use of an assistive device and (2) were able to maintain bilateral, quiet, upright stance for 10 s and (3) attended at least 2 of the testing sessions. Potential subjects were excluded if they (1) had experienced or been diagnosed with pain or degeneration of any other lower extremity joint (ipsilateral or contralateral), (2) had a previous ankle arthrodesis, (3) had a history of lower extremity joint arthroplasty or spinal surgery, or (4) any other neuromuscular deficiencies that could affect their activities of daily living or postural stability. At each assessment, participant anthropometric measurements were recorded including: height, weight, foot length, and foot width. Additionally, age at the time of surgery was determined from patient medical records and confirmed by patient self-report. The institutional review board approved the experimental protocol and all participants gave written informed consent prior to participation in this study.

Each participant was asked to perform three 10-s, quiet standing trials while barefoot in two experimental conditions: feet together (FT) and feet shoulder width (SW). The FT condition was characterized by the participant standing with their feet together and medial malleoli touching. The SW condition was characterized by participants standing with their feet at approximately shoulder width while their feet were aligned with the sagittal plane axis. Each foot was placed on an isolated force platform.

Ground reaction force (GRF) data were recorded from force platforms located beneath each foot (1200 Hz, BP600-900, AMTI, Watertown, MA, USA). Raw GRF data were filtered using a 4th order, zero-lag low-pass Butterworth filter with a cutoff frequency of 30 Hz (Bohn et al., 2016; Cavalheiro et al., 2009) and analyzed using custom software (MATLAB, Mathworks, Natick, MA). The cut-off frequency implemented in the current study is lower than previous research, however, the lower frequency of GRF data during quiet standing requires a lower cutoff frequency be used due to the less dynamic nature of movement. The filtered force platform data were used to calculate the coordinates of the center of pressure from each trial as described by Hufscmidt et al. (1980). COP excursions in the anteroposterior (AP) and mediolateral (ML) directions as well as the resultant distance (RD) were calculated as described by Prieto et al. (1996). COP excursion is a common measure of postural stability and represents the magnitude and direction of COP motion. The total AP and ML excursions were calculated according to Eq. (1) (Prieto et al., 1996):

$$TOTEX_{AP} = \sum_{n=1}^{N-1} |AP[n+1] - AP[n]| \quad (1)$$

where N is the total number of data points collected, and AP is the location in the AP plane of the COP at time point n. A similar equation is used for ML excursions. Similarly, the total excursion lengths were calculated according to Eq. (2) (Prieto et al., 1996):

Table 1
Patient demographics.

Variable	Mean	Std. dev.	Min	Max
Age at surgery (years)	63.39	9.78	25.07	83.41
1-Year test age (years)	64.73	9.64	33.52	84.41
2-Year test age (years)	65.32	10.21	27.07	85.41
Height (m)	1.71	0.10	1.40	2.05
Mass (kg)	86.74	18.03	49.80	145.0
BMI	29.58	5.55	18.29	51.37

$$EXCtotal = \sum_{n=1}^{N-1} \left[(AP[n+1] - AP[n])^2 + (ML[n+1] - ML[n])^2 \right]^{1/2} \quad (2)$$

The instantaneous COP velocity was calculated by taking the first derivative of the AP and ML COP position data, respectively. Mean excursion velocities (MEV) were calculated from the instantaneous COP velocity data. COP velocity has been shown to be a reliable and sensitive measure of postural stability in quiet standing (Sobanska et al., 2016). In addition to COP related measures, limb load magnitude was quantified as the mean vertical GRF recorded beneath each limb during the quiet standing trial. GRF values used to assess limb loading were normalized to body mass. Using body weight-normalized vertical GRF, an asymmetry index (AI) was calculated to assess the magnitude of asymmetry as described by Eq. (3) (Herzog et al., 1989; Robinson et al., 1987):

$$AI = \frac{F_{Surg} - F_{non-surg}}{1/2(F_{surg} + F_{non-surg})} \quad (3)$$

where F is the vertical GRF in each limb.

Variables of interest included surgical and non-surgical mean vertical GRF (and associated AI), COP excursions (AP and ML) and MEV (AP and ML) in the surgical and non-surgical limbs when participants performed quiet standing in the FT and SW conditions. Data were compared across the three time points (PRE, 1YR, 2YR) using a linear mixed effects, maximum likelihood estimation model with time and limb as main effects and sex, age at testing, and BMI as covariates. This model was chosen over a repeated measures ANOVA due to the number of participants who did not return for testing session at 1YR and 2YR time points or were not able to complete all tasks at each session. The maximum likelihood estimation solution to the mixed effects model accounts for missing data across different time points and still includes participants in the analysis who have completed at least one testing session. Normality of each variable was assessed using histograms and distributions were determined to be sufficiently normal for parametric analysis. All statistical analyses were conducted using STATA (StataCorp LLC, College Station, TX). Significance was set at $P < 0.05$ for all tests.

3. Results

Across the course of the study there were some subjects who were lost to follow-up and did not return at either one or both post-operative time points. In addition, there were some subjects that were unable to complete testing based on pain and disability; therefore the final analysis included 390 participants at the pre-op time point, 251 at the 1 year post-op time point, and 161 at the 2-year post-op time point.

Some of the data for COP measures of interest (AP and ML mean excursion – EXC – and AP and ML mean excursion velocity – MEV) supported our hypothesis. In the feet together condition, surgical limb EXC (Fig. 1) decreased with time (AP/ML: $P < 0.001$) while only ML EXC increased in the non-surgical limb with time

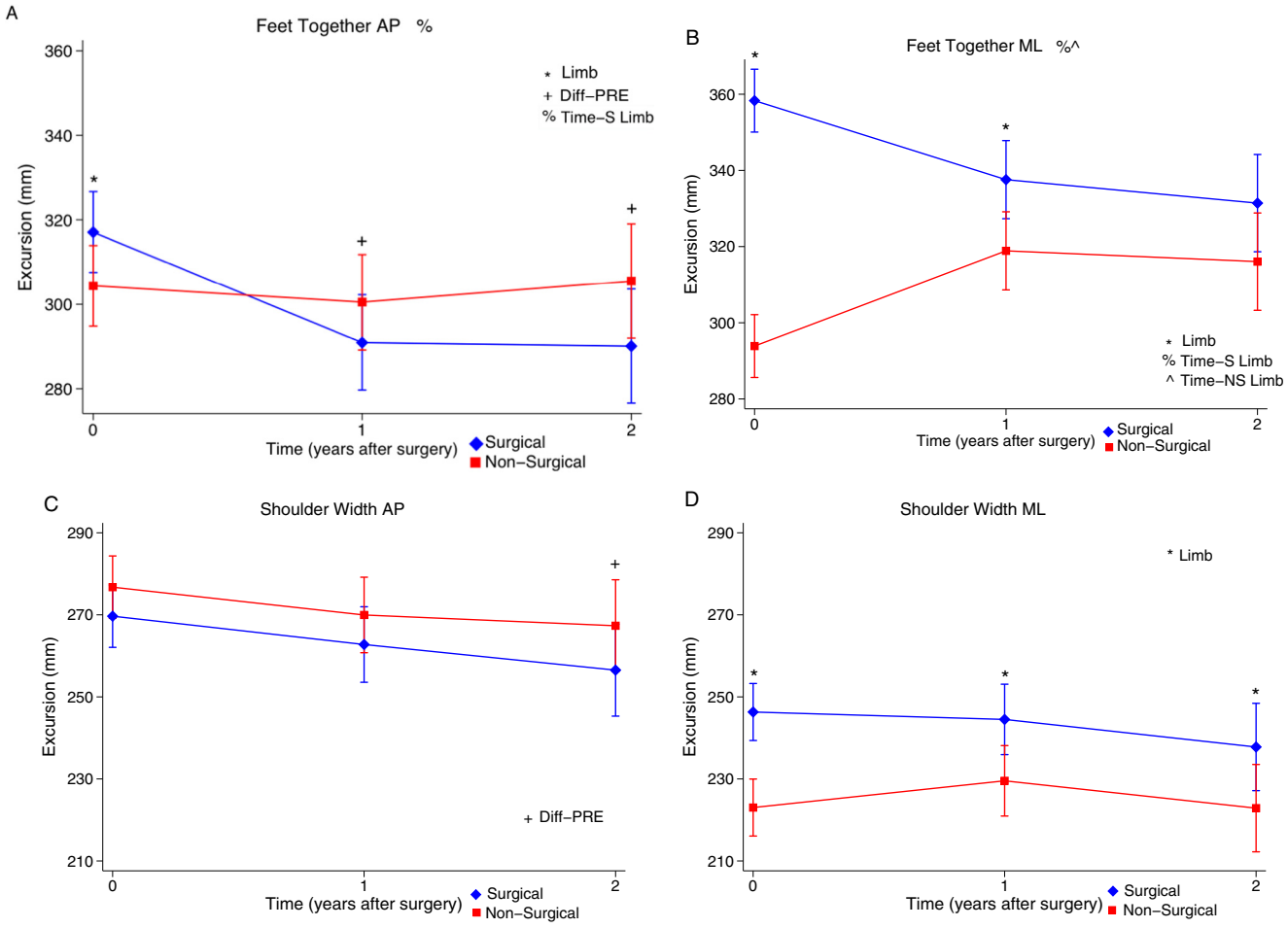

Fig. 1. Center of pressure excursion. AP and ML Center of Pressure excursions for surgical and non-surgical limbs in a,b) Feet Together and c,d) Shoulder Width conditions. Symbols correspond to significant effect as described by the legend.

(AP: $P = 0.751$, ML: $P < 0.001$). There were no significant main effects in MEV (Fig. 2). However, there were a number of differences between the surgical and non-surgical limb. Compared to the non-surgical limb, the surgical limb showed greater AP EXC ($P = 0.015$) at PRE and ML EXC at PRE ($P < 0.001$) and 1YR ($P = 0.008$) in the FT condition. In the SW condition, the surgical limb showed greater ML EXC than the non-surgical limb at all three time points (PRE: $P < 0.001$, 1YR: $P = 0.009$, 2YR: $P = 0.038$). MEV was only greater in the surgical limb in the ML direction at 2YR ($P = 0.031$).

Ground reaction forces (GRFs) changed consistently at each time point in the both limbs and were not significantly different between limbs by 2YR (Fig. 3). In the FT and SW conditions, there was a significant main effect interaction between time and limb (FT/SW: $P < 0.001$) and a significant main effect for limb itself ($P < 0.001$). In the FT condition, non-surgical GRFs were significantly greater than in the surgical limb at both PRE and 1YR time points (PRE/1YR: $P < 0.001$). At 2YR, there was no significant difference between the surgical and non-surgical limbs ($P = 0.201$). In the SW condition, the non-surgical limb force increased at each time point (PRE/1YR: $P < 0.001$, 2YR: $P = 0.014$). Furthermore, magnitude of AI for vertical GRF decreased at each time point in both FT and SW conditions between PRE and 1YR (all $P < 0.001$) and PRE and 2YR (all $P < 0.001$). In the FT condition, the AI (Table 2) was not significantly different from 0 (0 representing perfect symmetry) by 2YR ($P = 0.290$), but was different from 0 in the SW condition ($P = 0.035$). The influence of loading asymmetry on total EXC (Table 3) is significantly greater in the surgical limb in both FT and SW conditions at the PRE timepoint ($P < 0.001$). However, there is no significant difference between the limbs at 1YR (FT: $P = 0.612$, SW: $P = 0.216$) or 2YR (FT: $P = 0.786$, SW: $P = 0.270$) time points.

4. Discussion

The purpose of this study was to examine changes in bilateral COP and GRF profiles over a two-year period of recovery following total ankle arthroplasty. The current findings partially supported the hypothesis that EXCs and MEVs would decrease with time. Although the surgical limb EXC did decrease as the hypothesis suggested, it only decreased in the FT condition and changes in the MEV were not significant. With recovery, EXC (AP and ML) were reduced in the surgical limb in the FT condition. Concurrent increases in ML EXC were observed in the non-surgical limb over the same period. At 2 years post-TAA, the only inter-limb differences in EXC were in the ML direction in the SW condition. These findings suggest that time is associated with improved stability in the surgical limb and asymmetry is reduced two years post-TAA. While there is limited research investigating postural stability in TAA patients, previous studies having have demonstrated meaningful improvements in ankle mechanics and other gait variables in TAA patients (Valderrabano et al., 2007). The results of this study show progressive improvements in measures of postural stability with recovery, suggesting that TAA and recovery have a positive effect on patients' postural stability, potentially reducing the risk of falling and fall-related increases in mortality (Hosseini and Hosseini, 2008).

GRF data support the hypothesis that symmetry would be restored with recovery. Specifically, GRFs in both limbs converged

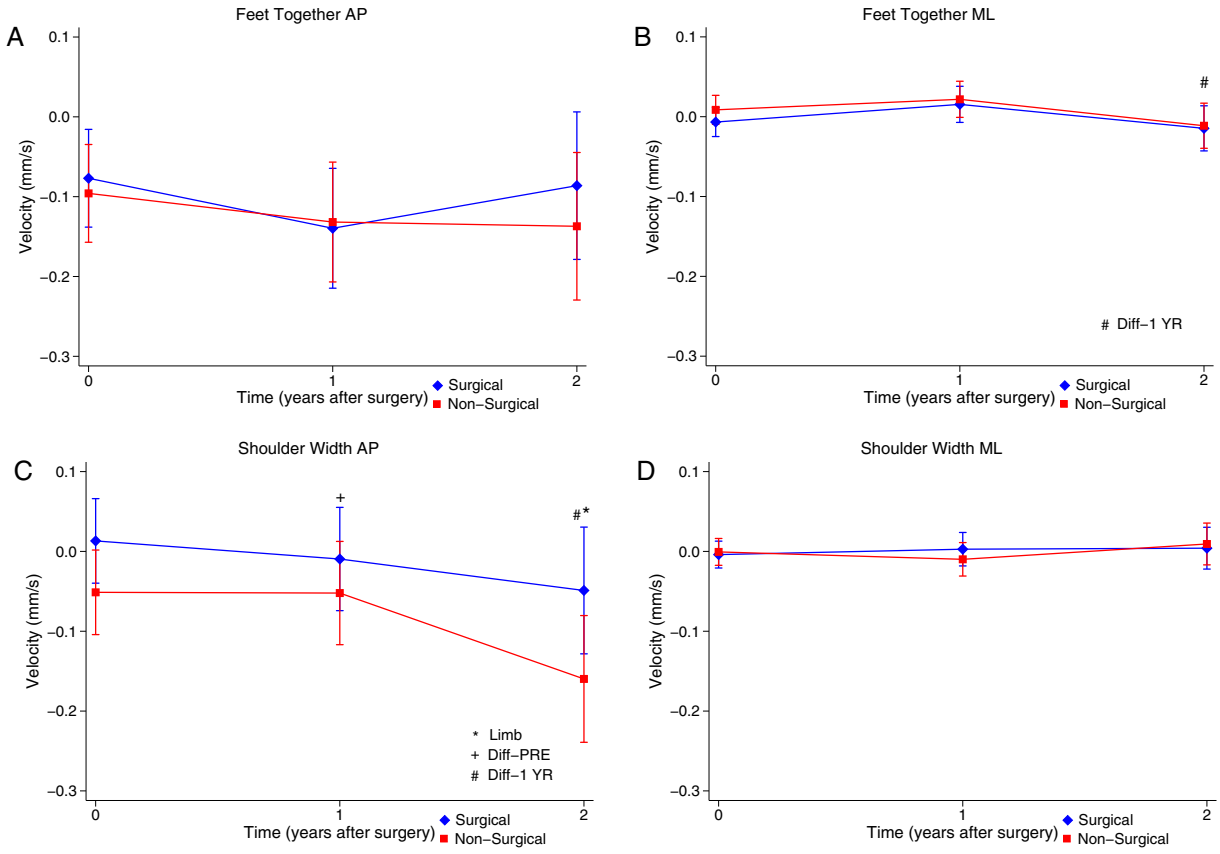

Fig. 2. Mean Center of pressure velocity. AP and ML mean COP Instantaneous Velocity for surgical and non-surgical limbs in a,b) Feet Together and c,d) Shoulder Width conditions. Symbols correspond to significant effect as described by the legend.

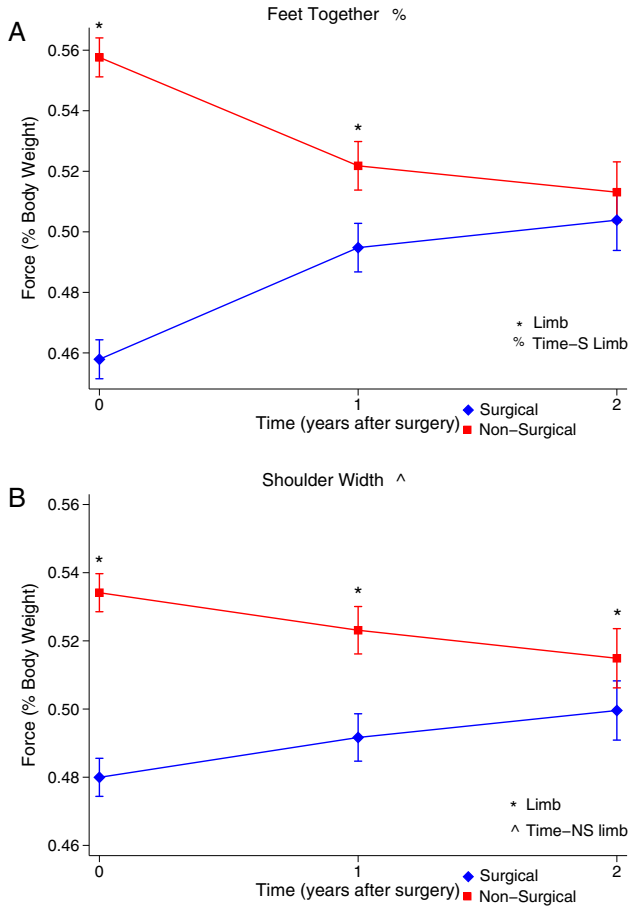

Fig. 3. Mean vertical ground reaction force. Mean vertical ground reaction force for surgical and non-surgical limbs in a) Feet Together and b) Shoulder Width conditions. Symbols correspond to significant effect as described by the legend.

toward 50% body weight, and AI of vertical GRF decreased with recovery. These findings support previous research that demonstrated that end-stage ankle OA patients (PRE) place increased load on their non-surgical limb (Horisberger et al., 2009). The associated decreases in non-surgical limb force coupled with increased loading in the surgical limb suggests that symmetry is being at least partially restored over time. Furthermore, increased loading symmetry has been linked with decreased fall risk in stroke patients (Cheng et al., 2001) and decreased postural stability in healthy patients (Anker et al., 2008). This suggests that the patients in this study may benefit from TAA in terms of decreasing fall risk and increasing postural stability. At 2 years post-surgery, no differences in vertical GRF were observed between the surgical and non-surgical limbs and the AI were not significantly different from 0 in the FT condition, which is the more challenging task. The decreases in resultant EXC in limbs with increased GRF agree with previous results that found higher EXC in the less loaded limb (Genthon and Rougier, 2005). It is also interesting to note that the change in resultant EXC with increased GRF asymmetry was greater in magnitude in the surgical limb than in the non-surgical only in the pre-op condition, suggesting that changes in loading symmetry affect the stability of the surgical limb more than in the non-surgical limb. Increased COP excursion has been linked with lower Berg Balance Scale (BBS) scores in an elderly population (Berg et al., 1992) and COP excursion has been shown to be reliable in differentiating between controls and patients with functional ankle instability, who are known to have postural stability deficits (Arnold et al., 2009; Ross et al., 2009). Furthermore, the difference in effect of loading asymmetry on excursion no longer exists after surgery. This suggests that a difference in loading asymmetry effect on COP excursion may be indicative of instability of the limb, instability of the patient, and increased risk of falls and injury. This could provide a valuable tool for analysis in patients with asymmetry in GRF or otherwise who may be candidates for TAA.

Though the current data present novel findings pertaining to the recovery of balance following TAA, the authors acknowledge several limitations. A significant number of patients were unable to attend or did not have usable data for all three visits. Therefore, not all patients included in the data analysis had usable data for all three visits, which may have affected the results. However, all patients included had data for the pre-op visit and at least 1 post-op visit. Although the pre-op data collection took place at most 2 weeks before each surgery, the exact windows of data collection for the post-op visits are unknown. Each patient only completed three trials in each condition. An increased number of trials for each condition would decrease the effects of outlying trials in which the patient was uncharacteristically unstable. Furthermore, each trial was only 10 s in length, which is not ideal for stability-based measures such as those described in this study. This was due to the inability of some patients to maintain quiet stance unassisted for much longer than that time. Other patients were excluded from the study because they were not able to maintain quiet stance for 10 s. Furthermore, the balance tests were conducted as part of the Short Physical Performance Battery (SPPB), which dictates 10 s trials. Longer trials may have improved the

Table 2
Asymmetry index for vertical ground reaction force (negative value indicates asymmetry favoring NS side). *-significant difference compared to 0 AI; +-significant difference compared to pre-op. P values describe comparisons to hypothetical mean of 0.

Condition	PRE LSI (SEM)	*P*	1YR LSI (SEM)	*P*	2YR LSI (SEM)	*P*
Feet Together	−0.197 (0.014) *	<0.001	−0.053 (0.014) +*	<0.001	−0.018 (0.016) +	0.262
Shoulder Width	−0.107 (0.013) *	<0.001	−0.062 (0.012) +*	<0.001	−0.030 (0.014) +*	0.034

Table 3
Regression slopes (mm / %BW) for resultant COP excursion v. vertical ground reaction force. * indicates significance difference between limbs. Slope data presented as mean (standard error of the mean). MD = absolute differences in mean slopes (and corresponding p-values) between S and NS side.

Condition	Limb	PRE slope (SEM)	PRE MD (*P*)	1YR slope (SEM)	1YR MD (*P*)	2YR slope (SEM)	2YR MD (*P*)
Feet together	S	−1196 (91.9) *	701 (< 0.001)	−675 (123.3)	36 (0.612)	−652 (172.9)	54 (0.786)
	NS	−405 (85.5) *	–	−711 (115.6)	–	−598 (143.8)	–
Shoulder width	S	−893 (83.1) *	550 (< 0.001)	−571 (136.7)	50 (0.216)	−496 (166.6)	33 (0.270)
	NS	−343 (84.5) *	–	−521 (137.0)	–	−529 (160.6)	–

robustness of the analysis, but a longer time was not feasible in this population. Additionally, the lack of a control group for comparison does not allow for comparison between the post-operative TAA patients an those who are age matched control subjects. Finally, it should be noted that very few results were found to be significant in the SW balance data. This is likely due to the difference in task difficulty between the FT and SW conditions. FT stance results in increased movements at the hip, knee, and ankle joints as well as increased center of gravity sway (Gatev et al., 1999). Additionally, more difficult stance conditions have greater sensitivity to detect changes, particularly in older adults (Salehi et al., 2010). Because FT is a more difficult condition than SW, it should be expected that the FT condition would have more significant results and be able to more easily detect changes in stability.

In summary, the results of this study suggest that there are significant recoveries in postural stability as TAA patients recover from surgery that tend to restore symmetry. The non-surgical limb may be more responsible for maintaining balance at first, but the contribution balances with the surgical limb over time. The causes of these changes are unclear – the ankle arthroplasty procedure could be removing mechanical hindrances that prevented patients from maintaining stability, or the patients' balance could be improving simply because they are no longer in as much pain. The differences in the effects of loading asymmetry between the surgical and non-surgical COP excursion at the pre-op time point could provide a valuable analysis tool to diagnose stability problems in patients who may have unilateral pathologies or neurological disorders that affect balance. Specifically, this difference could indicate that the improvements in balance seen after recovery may be due to a decreased reliance on the non-surgical limb, resulting in the equality of the excursion-GRF slopes. Future work could expand upon the number of trials collected in these patients and further examine the changes in the effect of loading asymmetry on COP excursion in different populations.

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Conflicts of Interest statement

None to declare

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