Clinical Biomechanics 30 (2015) 636–639

Contents lists available at ScienceDirect

Clinical Biomechanics

journal homepage: www.elsevier.com/locate/clinbiomech

Brief report

Inter-joint coordination strategies during unilateral stance following first-time, acute lateral ankle sprain: A brief report

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ARTICLE INFO

Article history:
Received 25 December 2014
Accepted 16 April 2015

Keywords:
Ankle joint
Biomechanical phenomena
Kinematics
Kinetics
Postural balance

ABSTRACT

Background: This investigation combined measures of inter-joint coordination and stabilometry to evaluate eyes-open (condition 1) and eyes-closed (condition 2) static unilateral stance performance in a group of participants with an acute, first-time lateral ankle sprain injury in comparison to a control group.
Methods: Sixty-six participants with an acute first-time lateral ankle sprain and 19 non-injured controls completed three 20-second unilateral stance task trials in conditions 1 and 2. An adjusted coefficient of multiple determination statistic was used to compare stance limb 3-D kinematic data for similarity in the aim of establishing patterns of inter-joint coordination for these groups.
Findings: Between-group analyses revealed significant differences in stance limb inter-joint coordination strategies for conditions 1 and 2. Injured participants displayed increases in ankle-hip linked coordination compared to controls in condition 1 (sagittal/frontal plane: 0.12 [0.09] vs 0.06 [0.04]; $\eta^2 = .16$) and condition 2 (sagittal/frontal plane: 0.18 [0.13] vs 0.08 [0.06]; $\eta^2 = 0.37$).
Interpretation: Participants with acute first-time lateral ankle sprain exhibit a hip-dominant coordination strategy for static unilateral stance compared to non-injured controls.

1. Introduction

Two recently published investigations from our research laboratory evaluated the movement patterns of individuals in the acute phase of, and 6 months following, a first-time lateral ankle sprain (LAS) injury (Doherty et al., 2014, 2015). Kinematic and stabilometric data were utilised in these investigations to quantify the coordination of postural control during the prescribed tasks of eyes-open and eyes-closed unilateral stance (Doherty et al., 2014, 2015). The latter of these investigations (Doherty et al., 2015) quantified the kinematics of inter-joint coordination for the stance limb utilising an adjusted coefficient of multiple determination (ACMD) statistic (Kadaba et al., 1989; Liu et al., 2012). The ACMD can be used to compare the similarity between two waveforms (Kadaba et al., 1989). In the aforementioned investigation, lower limb 3-D angular displacement waveforms during 20 s of unilateral stance were compared for similarity in such a manner. We believed that this method of analysis would identify compensatory joint 'coupling' movement strategies in response to the somatosensory compromise of the injured ankle joint (Evans et al., 2004; Freeman, 1965; McKeon et al., 2012). The findings of the investigation elucidated that LAS participants display increased ankle-hip linked coordination patterns during unilateral stance in both the presence and absence of vision (Doherty et al., 2015). Specifically, LAS participants displayed greater 'coupling' of sagittal plane hip motion with both frontal and transverse plane ankle motion in the eyes-open condition (Doherty et al., 2015). In the eyes-closed condition, LAS participants displayed greater coupling of sagittal plane hip motion with frontal plane ankle motion (Doherty et al., 2015). LAS participants also exhibited significantly greater range of motion at the ankle joint in the eyes-open condition, and significantly greater range of motion at the hip joint in the sagittal plane in the eyes-closed condition (Doherty et al., 2015). Based on these findings, we theorised that a hip-centred postural control strategy was adopted in the LAS group due to the local somatosensory compromise associated with reduced ankle joint function, and that this was magnified on removal of visual afferents. We believed this theory to be confirmed by the increase in range of motion exhibited at the hip and ankle joints by LAS participants (Doherty et al., 2015).

The kinematic analysis completed on this cohort in the acute phase of injury elucidated that, in the 2-week window following acute LAS,

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http://dx.doi.org/10.1016/j.clinbiomech.2015.04.012
0268-0033/

individuals adopt a position of increased hip flexion during eyes-closed unilateral stance; inter-joint coordination was not evaluated (Doherty et al., 2014).

Therefore, application of the same analysis techniques utilised in the 6-month investigation (ACMD statistic and calculation of joint ranges) to the data collected from the acute experiment stands to advance current understanding of the acute effects of LAS on unilateral stance coordination strategies in the presence and absence of vision, and may unearth a potential link to the findings of the 6-month study. The current paper is a brief report of this analysis: data collected and recently published from the LAS participants in the acute phase of injury (Doherty et al., 2014) were re-analysed in line with the techniques described in the 6-month paper (Doherty et al., 2015) to quantify inter-joint coordination strategies during the unilateral stance tasks.

2. Methods

2.1. Participants

Data collected from the same sixty-six participants within 2-weeks of sustaining an acute first-time LAS and nineteen uninjured participants previously described (Doherty et al., 2014) were utilised for analysis.

2.2. Protocol

Briefly, participants were instrumented with the Codamotion bilateral lower limb gait set-up according to manufacturer guidelines (Charnwood Dynamics Ltd, Leicestershire, UK) (Doherty et al., 2014) following the collection of anthropometric measures required for the calculation of internal joint centres of the lower extremity joints. Participants then performed three, 20-second trials of quiet unilateral stance barefoot on a force-plate with their eyes open on both limbs, during which kinematic data for the current analysis was acquired. Following another 2 minute rest period, participants then attempted to complete three, 20-second trials of the quiet unilateral stance task with their eyes closed.

2.3. Kinematic and kinetic data processing

Three Codamotion cx1 units were used to provide information on 3-D angular displacements at the hip, knee and ankle joints for both limbs during the unilateral stance task. Kinematic data acquisition was made at 100 Hz.

Kinematic data were calculated by comparing the angular orientations of the coordinate systems of adjacent limb segments using the angular coupling set "Euler angles" to represent clinical rotations in three dimensions.

Pairwise comparison of 3-D temporal angular displacement waveforms for the hip, knee and ankle joints of the stance limb were made using the ACMD statistic (Kadaba et al., 1989) as previously described (Doherty et al., 2015). Mean values of all joint angular ranges (maximum value − minimum value) during testing in each task were computed for comparisons between LAS and control participants (Doherty et al., 2015).

2.4. Data analysis and statistics

For the LAS group, the limb injured at the time of recruitment was labelled as "involved" and the non-injured limb as "uninvolved". In all cases the limbs in the control group were side matched to the injured group. For all outcomes, we calculated mean (SD) scores for the involved and uninvolved limbs in the LAS group, and mean (SD) scores for the left and right limbs in the control group.

We undertook a series of independent sample t-tests comparing: involved limb vs control, and uninvolved limb vs control. The dependent variables were the pairwise comparison ACMD statistic values between waveforms for each joint in each plane of motion in the eyes-open and eyes-closed conditions. Furthermore, the mean joint range of motion in both conditions was computed for all joints in all planes for comparison between LAS and control groups. The significance level for these analyses were adjusted for multiple tests using the Benjamini–Hochberg method for false discovery rate (<5%) (Benjamini and Hochberg, 1995) in two groups (ACMD and joint ranges) each with two levels (eyes-open and eyes closed).

All data were analysed using Predictive Analytics Software (Version 18, SPSS Inc., Chicago, IL, USA).

3. Results

The LAS group displayed significantly greater similarities in joint angular motions based on ACMD values between sagittal plane hip

Table 1
Mean ACMD values with associated SDs and *P*-values for both the involved and uninvolved limbs of LAS and control participants in the eyes-open condition.

Joint pair		Eyes open														
		Hip/ankle					Knee/ankle					Hip/knee				
		LAS		Control			LAS		Control			LAS		Control		
		Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value
Involved	F/F	.18	.15	.15	.12	0.372	.18	.17	.14	.12	0.364	.20	.20	.15	.14	0.380
	F/S	.18	.13	.16	.12	0.486	.24	.17	.25	.23	0.730	.19	.15	.18	.14	0.884
	F/T	.27	.18	.21	.17	0.173	.15	.16	.16	.11	0.815	.19	.19	.12	.10	0.037
	S/F	.12	.09	.06	.04	0.001*	.16	.14	.12	.11	0.282	.18	.18	.15	.08	0.268
	S/S	.21	.20	.18	.14	0.422	.57	.26	.60	.22	0.630	.34	.24	.27	.16	0.141
	S/T	.10	.10	.09	.05	0.462	.14	.13	.11	.10	0.478	.17	.17	.11	.08	0.172
	T/F	.32	.21	.33	.21	0.833	.20	.18	.28	.17	0.090	.20	.18	.26	.15	0.199
	T/S	.16	.13	.17	.13	0.836	.21	.17	.16	.13	0.241	.18	.14	.17	.15	0.802
	T/T	.39	.23	.41	.22	0.664	.31	.20	.41	.21	0.065	.26	.19	.27	.17	0.731
Uninvolved	F/F	.17	.14	.19	.15	0.610	.21	.18	.15	.13	0.204	.20	.17	.16	.13	0.353
	F/S	.16	.13	.25	.20	0.076	.22	.19	.22	.16	0.947	.19	.15	.20	.14	0.921
	F/T	.23	.14	.24	.17	0.835	.15	.12	.17	.13	0.544	.16	.13	.13	.09	0.434
	S/F	.11	.09	.11	.08	0.867	.19	.15	.19	.15	0.983	.18	.16	.20	.14	0.675
	S/S	.18	.16	.23	.12	0.230	.56	.21	.57	.23	0.845	.29	.19	.25	.16	0.421
	S/T	.13	.10	.13	.15	0.986	.16	.11	.16	.09	0.835	.14	.11	.14	.09	0.877
	T/F	.29	.21	.26	.16	0.497	.21	.17	.17	.14	0.384	.22	.16	.20	.20	0.662
	T/S	.14	.11	.16	.11	0.461	.19	.13	.23	.16	0.244	.16	.13	.16	.11	0.937
	T/T	.40	.21	.32	.23	0.112	.33	.22	.38	.29	0.394	.27	.19	.23	.19	0.383

'/' denotes comparison between two joints/planes of motion. Abbreviations: ACMD = adjusted coefficient of multiple determination; LAS = lateral ankle sprain; SD = standard deviation; F = frontal plane of motion; S = sagittal plane of motion; T = transverse plane of motion.
* Denotes statistically significant between-groups difference.

Table 2
Mean ACMD values with associated SDs and *P*-values for both the involved and uninvolved limbs of LAS and control participants in the eyes-closed condition.

Joint pair		Eyes closed														
		Hip/ankle					Knee/ankle					Hip/knee				
		LAS		Control			LAS		Control			LAS		Control		
		Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value
Involved	F/F	.26	.14	.18	.12	0.065	.20	.12	.22	.22	0.725	.24	.24	.20	.15	0.570
	F/S	.15	.10	.12	.12	0.402	.19	.14	.19	.13	0.907	.16	.14	.13	.10	0.568
	F/T	.33	.16	.23	.12	0.041	.20	.19	.24	.24	0.565	.14	.13	.15	.13	0.799
	S/F	.18	.13	.08	.06	0.001*	.15	.10	.11	.09	0.133	.18	.16	.22	.19	0.268
	S/S	.17	.17	.24	.19	0.207	.49	.19	.45	.20	0.615	.30	.24	.33	.20	0.141
	S/T	.13	.12	.11	.08	0.514	.13	.12	.11	.12	0.612	.11	.11	.16	.09	0.172
	T/F	.34	.23	.36	.27	0.772	.23	.17	.25	.25	0.756	.18	.20	.36	.26	0.017
	T/S	.14	.13	.11	.10	0.498	.17	.13	.20	.12	0.539	.13	.12	.15	.15	0.652
	T/T	.42	.27	.42	.33	0.995	.33	.23	.36	.27	0.709	.35	.21	.31	.32	0.704
Uninvolved	F/F	.22	.18	.26	.19	0.433	.21	.18	.11	.13	0.041	.23	.18	.24	.18	0.910
	F/S	.17	.16	.16	.13	0.733	.20	.17	.18	.15	0.730	.15	.13	.19	.13	0.378
	F/T	.30	.16	.29	.16	0.859	.15	.13	.15	.15	0.954	.16	.15	.12	.10	0.155
	S/F	.15	.12	.08	.06	0.014	.15	.13	.11	.09	0.231	.22	.19	.19	.16	0.566
	S/S	.20	.15	.19	.19	0.797	.51	.21	.52	.22	0.817	.29	.22	.28	.22	0.919
	S/T	.13	.10	.09	.07	0.111	.12	.09	.08	.07	0.074	.14	.13	.11	.07	0.315
	T/F	.36	.24	.37	.23	0.822	.29	.23	.18	.16	0.089	.22	.17	.29	.20	0.159
	T/S	.13	.13	.16	.11	0.430	.19	.18	.16	.14	0.559	.17	.13	.14	.11	0.309
	T/T	.43	.25	.43	.25	0.966	.36	.24	.38	.25	0.794	.37	.19	.27	.20	0.108

'/' denotes comparison between two joints/planes of motion. Abbreviations: ACMD = adjusted coefficient of multiple determination; LAS = lateral ankle sprain; SD = standard deviation; F = frontal plane of motion; S = sagittal plane of motion; T = transverse plane of motion.
* Denotes statistically significant between-groups difference.

motion and frontal plane ankle motion on their involved limb in the eyes-open and eyes-closed conditions (Table 1: eyes open; Table 2: eyes closed). LAS participants also exhibited an altered range of motion at a number of joints on both their involved and uninvolved limbs compared to control participants (Table 3).

4. Discussion

The purpose of this brief report was to 'update' the analyses utilised in a previously published study of participants with first-time acute LAS (Doherty et al., 2014), in line with those we more recently adopted for the same cohort 6 months following this injury (Doherty et al., 2015). The seemingly greater 'coupling' between sagittal plane hip motion and frontal plane ankle motion displayed by LAS participants in the current investigation suggests that these individuals re-weight reliance on a more proximal joint (the hip) to compensate for reduced function at the ankle joint, which is typically responsible for the fine-tuned low amplitude movements required for completion of static postural control tasks (Nashner and McCollum, 1985; Tropp and Odenrick, 1988).

Nashner and McCollum were the first to propose the presence of two primary coordination strategies that can be used either independently or in conjunction by the central motor programme for maintaining postural control (Nashner and McCollum, 1985). These strategies are then 'chosen' on the basis of afferent feedback received from sensory receptors and the constraints affecting the organism (Nashner and McCollum, 1985). For example, it is generally recognised that the ankle joint is appropriate for subtle changes in postural control. Conversely, the 'hip strategy' is recruited to compensate for more substantial disturbances in equilibrium (Nashner and McCollum, 1985; Hwang et al., 2009). This has been confirmed by Tropp and Odenrick (Tropp and Odenrick, 1988), who observed a central role of the ankle joint in postural corrections during single-limb standing, which is

Table 3
Mean joint angular range values with associated SDs and *P*-values for both the involved and uninvolved limbs of LAS and control participants in the eyes-open and eyes-closed conditions. Values are reported in degrees.

		Eyes open														
		Hip					Knee					Ankle				
		LAS		Control			LAS		Control			LAS		Control		
		Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value	Mean	SD	Mean	SD	*P*-value
Involved	F	5.24	3.88	3.86	3.70	0.165	2.38	2.76	2.03	1.82	0.600	15.26	24.45	5.70	2.35	0.003*
	S	5.66	5.17	3.27	2.69	0.051	8.04	8.85	5.27	3.01	0.174	6.34	8.49	4.17	2.66	0.265
	T	6.93	4.44	5.80	3.97	0.314	6.63	10.21	4.27	3.26	0.313	9.55	9.00	6.04	1.84	0.004*
Uninvolved	F	3.64	2.32	9.51	6.08	0.001*	2.13	2.54	4.22	4.27	0.010*	10.23	11.19	9.76	4.09	0.874
	S	4.28	5.22	10.13	9.36	0.023*	6.23	4.94	9.69	6.28	0.016*	8.93	28.67	6.63	3.36	0.743
	T	6.02	3.15	14.16	8.37	0.001*	4.75	3.94	7.58	5.81	0.018*	7.87	4.17	12.51	4.95	0.000*
Eyes closed																
Involved	F	8.87	4.99	3.24	1.64	0.000*	4.24	3.77	2.11	1.77	0.006*	19.64	16.02	4.99	2.75	0.000*
	S	9.90	11.39	3.19	1.06	0.001*	11.10	6.80	5.93	2.88	0.000*	9.64	10.87	4.30	2.43	0.035
	T	11.69	4.97	5.14	2.89	0.000*	10.39	10.55	6.58	4.84	0.133	13.93	5.43	7.77	4.31	0.000*
Uninvolved	F	9.11	6.35	7.87	4.55	0.521	3.82	4.37	3.35	3.61	0.722	15.08	13.55	12.01	7.13	0.467
	S	6.94	4.97	8.69	6.75	0.343	8.66	6.12	8.06	5.65	0.757	6.32	5.09	9.68	14.30	0.285
	T	11.14	7.01	11.95	7.19	0.722	7.37	8.08	14.13	20.42	0.140	14.62	9.29	18.44	14.13	0.297

Abbreviations: LAS = lateral ankle sprain; SD = standard deviation; F = frontal plane of motion; S = sagittal plane of motion; T = transverse plane of motion.
* Denotes statistically significant between-groups difference.

impaired in individuals suffering from chronic, long term sequalae following a LAS. Their findings, and those of the current report, lend to the hypothesis that the trauma associated with an acute LAS injury may distort the sensory afferents from the ankle capsular, ligamentous and muscular structures (McKeon et al., 2012; McCollum et al., 1996), thus forcing individuals to adopt more proximal strategies to safely maintain unilateral stance. Perhaps the adoption of a hip-dominant strategy is merely a 'next-in-line' strategy to adjust for the impaired ankle; the increase in involved limb frontal and transverse plane ankle motion in LAS participants during eyes-open SLS may represent a lack of control, which could only be compensated for at the hip. Similarly, this trend was also present in the eyes-closed condition, and further coupled with an increase in hip motion, lending to this hypothesis. That many of the same inter-joint coordination strategies exist in individuals, 6 months following the initial injury (Doherty et al., 2015) highlights the potential for acute deficits to persist in the 'recovery' period. However, this study is limited in that it is unknown as to whether these deficits actually predicated the LAS in the first instance, or manifested following. While previously completed longitudinal studies have utilised stabilometric measures to quantify the degeneration of postural control that is associated with LAS (Evans et al., 2004), future studies are required to clarify this issue from a kinematic perspective.

5. Conclusions

In conclusion, this report advances our current understanding of the effect of LAS injury on the coordination of eyes-open and eyes-closed postural control. We believe the use of the ACMD statistic better quantifies the coordination strategies required for static postural control tasks; hence the worth of the current report in updating our previously published findings.

Conflicts of interest and source of funding

No conflicts of interest were associated with the authors and the results of this research.

Acknowledgements

This study was supported by the Health Research Board (HRA_POR/2011/46) as follows: PI — Eamonn Delahunt; co-investigators — Chris Bleakley and Jay Hertel; PhD student — Cailbhe Doherty.

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