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Rate of loading, but not lower limb kinematics or muscle activity, is moderated by limb and aerial variation when surfers land aerials

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ABSTRACT

We aimed to determine whether there were any differences in how surfers used their lead and trail limbs when landing two variations of a simulated aerial manoeuvre, and whether technique affected the forces generated at landing. Fifteen competitive surfers (age 20.3 ± 5.6 years, height 178.2 ± 9.16 cm, mass 71.0 ± 10.5 kg) performed a Frontside Air (FA) and Frontside Air Reverse (FAR), while we collected the impact forces, ankle and knee muscle activity, and kinematic data. A principal component analysis (PCA) was used to reduce 41 dependent variables into 10 components. A two-way MANOVA revealed that although there were no limb x aerial variation interactions, surfers generated significantly higher relative loading rates at landing for the trail limb compared to the lead limb (+28.8 BW/s; $F_{(1,303)} = 20.660$, $p < 0.0001$, $\eta^2 = 0.064$). This was likely due to the surfers "slapping" the trail limb down when landing, rather than controlling placement of the limb. Similarly, higher relative loading rates were generated when landing the FA compared to the FAR (+23.6 BW/s; $F_{(1,303)} = 31.655$, $p < 0.0001$, $\eta^2 = 0.095$), due to less time over which the forces could be dissipated. No relationships between aerial variation or limb were found for any of the kinematic or muscle activity data. Practitioners should consider the higher relative loading rates generated by a surfer's trail limb and when surfers perform a FA when designing dry-land training to improve the aerial performance of surfing athletes.

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KEYWORDS
aerial manoeuvres; Athletic performance; loading rate; surfing; water sports

Introduction

Surfing athletes will compete in the Olympic Games for the first time in 2021 in Tokyo, increasing the sport's profile globally (20). This recent increase in the sport's worldwide exposure has been accompanied by a concurrent rise in surfing-related research (Pérez-Gutiérrez & Cobo-Corrales, 2020), with several publications highlighting how complex manoeuvres, such as aerials, can improve a surfer's winning potential during competitions (Ferrier et al., 2018; Forsyth et al., 2017; Lundgren, Newton et al., 2014). Aerials, where surfers launch themselves and their surfboard into the air before landing back on the crest or face of the wave, score well in surfing competitions because of the difficulty and high risk involved in successfully completing them. During surfing competitions, both the Frontside Air and Frontside Air Reverse have been highlighted as aerial variations that are likely to be highly rewarded by judges (Ferrier et al., 2018; Forsyth et al., 2017). Aerials have also been linked to injury (Furness et al., 2015; Lundgren, Butel et al., 2014; Minghelli et al., 2018; Nathanson et al., 2007, 2002), particularly soft tissue injuries to the ankle (Furness et al., 2015; Hohn et al., 2020; Lundgren, Butel et al., 2014) and knee joint (Hohn et al., 2020; Inada et al., 2018). It is therefore imperative that we understand how surfers can successfully perform aerials while reducing the risk of injury associated with completing these manoeuvres (Forsyth et al., 2020a).

Previous research has revealed that surfers display distinctly different loading strategies and ankle joint motion when landing aerials compared to when completing traditional drop landings (Lundgren et al., 2016). For example, compared to drop landings, when landing simulated, dry-land aerial surfers displayed significantly greater peak tibial accelerations (pooled mean ± standard deviation: aerial landing 15.7 ± 2.6 g vs drop landing 9.2 ± 2.4 g) and moved through significantly less percentage of their static ankle range of motion in their lead (front) limb (aerial landing 66.3% vs drop landing 81.3%) (LE Lundgren et al., 2016). Landing with the lead ankle in dorsiflexion at initial board-wave contact, rather than the plantar flexed alignment typically displayed during drop landings (Niu et al., 2011; Whitting et al., 2007, 2011), has also been associated with successfully performing the Frontside Air and Frontside Air Reverse in the ocean during surfing competitions (Forsyth et al., 2018). Using a restricted range of ankle motion and a dorsiflexed alignment when landing aerials is likely due to a surfer's need to maintain contact with the deck of their surfboard to successfully complete the task (LE Lundgren et al., 2016).

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Landing on a surfboard also requires surfers to adopt an asymmetrical stance, with one limb, the lead limb, ahead of the rear or trail limb. Although a surfer's lead and trail ankles are usually both dorsiflexed at initial contact during simulated aerial tasks, the lead ankle usually has a significantly greater dorsiflexion angle at initial contact when they perform a Frontside Air Reverse compared to a Frontside Air (Forsyth et al., 2020b). Furthermore, when performing a Frontside Air Reverse surfers displayed approximately 10° less knee extension of the lead limb at initial board-ground contact compared to the trail limb, reducing the total available range of knee joint motion over which to dissipate the forces generated at landing (Forsyth et al., 2020b). Researchers have previously suggested that how surfers use their lead and trail limbs during surfing manoeuvres might play a role in the type or location of injury they sustain. In an analysis of surfing injuries incurred by 86 professional surfers who presented to a single orthopaedic centre between 1991 and 2016, 62% of medial collateral ligament injuries occurred in the lead limb, whereas 71% of meniscal tears occurred in the trail limb (Hohn et al., 2020). Ankle sprains and high ankle sprains occurred significantly more frequently in the trail limb (69–73%) compared to the lead limb (Hohn et al., 2020). No previous research was located, however, that has examined how surfers control their lead and trail limbs when landing aerial manoeuvres or how their landing technique affects the potential for incurring a lower limb injury.

Previous biomechanical analyses of land-based landing tasks have identified inter-limb differences that are either task-related (Harry et al., 2018) or influenced by limb dominance (Edwards et al., 2012; Niu et al., 2011; Wang & Fu, 2019). For example, when performing a step-off drop landing, 10 healthy adults displayed significantly greater flexion of their trail limb knee at initial foot-ground contact (22.3° ± 9.8°) compared to their lead limb (12.2° ± 7.7°) (Harry et al., 2018). This resulted in less angular displacement at the knee between impact and the time of the peak ground reaction force, likely contributing to the higher relative landing forces generated by the participants and potentially increasing the risk of sustaining an injury to the trail limb (Harry et al., 2018). In a study of 16 basketball and soccer players performing a stop-jump task, the participants exhibited significantly different amounts of knee flexion when comparing their dominant and non-dominant limbs during the task (Edwards et al., 2012). More specifically, during the horizontal landing phase of the stop jump task, the participants displayed significantly lower knee flexion of their dominant limb, which resulted in significantly higher peak patellar tendon forces, higher knee joint moments, and faster loading rates compared to their non-dominant limb. Interestingly, the authors noted that the differences in knee joint kinematics and kinetics were not reflected in any differences in the timing of when the participants recruited their lower limb muscles (Edwards et al., 2012). Similarly, when 16 healthy adults landed from different heights (0.32 m – 0.72 m), there were no differences between the participants' dominant and non-dominant limbs in terms of the onset of tibialis anterior or lateral gastrocnemius (Niu et al., 2011). The participants, however, displayed significantly greater intensity of the non-dominant limb tibialis anterior in the 100 ms prior to and 100 ms following initial contact compared to the dominant limb, accompanied by significantly lower peak angular dorsiflexion velocity (Niu et al., 2011). Given that board sports, particularly surfing, have clearly defined and differentiated roles for the lead and trail limbs (Anthony et al., 2016; Furley et al., 2018; Staniszewski et al., 2016), similar inter-limb differences in muscular control are likely to be seen when surfers perform different aerial manoeuvres, although this notion has not been investigated.

Aerial landings in surfing are distinctly different to landings performed in other land-based sports because a surfer's landing technique is restricted by the need to land on a narrow, moving object – a surfboard (Forsyth et al., 2018, 2020b; Lundgren et al., 2016). Although it is evident that landing aerials on a surfboard constrains the technique a surfer can use, no published study was located that has comprehensively examined the biomechanics of how surfers use their lead and trail limbs when landing different variations of aerial manoeuvres and how their technique affects the forces generated at landing. The aim of the present study was therefore to determine whether there were any differences in the biomechanics of how surfers used their lead and trail limbs when landing two variations of a simulated aerial manoeuvre, and whether a surfer's technique affected the forces generated at landing. We hypothesized that the surfers would have different kinematic and muscle activation patterns in the lead and trail limb to prepare for and execute an asymmetrical landing, and that this would be moderated by the aerial variation performed. Furthermore, these asymmetrical landing strategies were hypothesized to influence the participants' ability to attenuate the forces generated at landing.

Methods

Participants

Fifteen highly skilled competitive male surfers (age: 20.3 ± 5.6 [range 15–35] years, height 178.2 ± 9.16 [range 156.5–195.8] cm, mass 71.0 ± 10.5 [range 44.8–80.9] kg) were recruited from the local area as study participants using advertisements on social media and by word of mouth. An a priori power analysis (G*Power, version 3.1.9.7) (Faul et al., 2007) estimated that a sample size of 15 participants was sufficient to identify differences in the outcome variables between different landing tasks (Whitting et al., 2009). The participants had previously competed in national level surfing competitions or above; reported surfing experience of 11.8 ± 6.7 years and practice times of 1.9 ± 0.8 hours/day, 6.1 ± 1.1 days/week; and were free from any lower limb injury at the time of testing. Each participant was informed of the potential risks associated with the study before providing written informed consent to participate. For participants below the age of 18, parental consent was also obtained. The research procedures were approved by the institution's Human Research Ethics Committee (HE16/133).

Procedures

Experimental Task. To ensure participants were adequately prepared to perform each experimental task, they completed a series of whole-body movements (squats, walking lunges, tuck jumps, and drop-and-stick landings). Five successful attempts of two variations of a surf-like simulated aerial landing were then performed: (i) a simulated Frontside Air (FA), and (ii) a simulated Frontside Air Reverse (FAR) (see Figure 1 and Figure 2). For both tasks, the participants approached a mini trampoline at a self-selected pace while carrying an instrumented, finless soft-top surfboard (Softech 5′4 TC Pro, Softech, Australia). The participants jumped off the trampoline and projected themselves into the air, before placing the surfboard underneath their feet and landing on a soft crash mat (polyurethane foam, 2750 × 1370 x 305 mm; Acromat, Australia). For the FA the participants performed the task with minimal rotation while in the air. For the FAR, the participants were required to rotate approximately 180° while in the air before landing. A trial was deemed successful if the participant was able to make contact with the surfboard before landing on the crash mat and maintain a stable position for approximately 3 seconds once they had landed. Each trial was filmed using an Apple iPad 4 (120 Hz; Apple, USA) placed on a tripod, which was approximately 5 m away from the midline of the crash mat at an angle of 35° so that the participant's vertical jump displacement could be estimated (Forsyth & Steele, 2020). Reliability of the vertical jump displacement estimates was found to be good (ICC = 0.853).

Forces Generated at Landing. Two flexible pressure mats (497 x 399 × 3 mm, mass = 900 g each; 200 Hz; Pliance® Novel$_{GmbH}$, Germany) were adhered to the deck of the soft-top surfboard, oriented to suit each participant's stance (see Figure 1). The deck of the foam surfboard had been planed so that the mats sat flush along the top of the board. Before performing a FA or FAR trial, the participants placed one foot on each pressure mat and stamped a foot three times in order to later time synchronize the force data with the kinematic and electromyography data, described below. The vertical forces, relative to the surfboard deck, generated during the landing phase of each FA and FAR trial were recorded using Pliance® software (version 25.3.6) and then exported to Excel and MATLAB (Mathworks, version R2019a) for later analysis. To align the three datasets, all three data sources were imported into a custom MATLAB script. For both the force and joint kinematics data, each dataset was first pre-processed so that the *zero* data point was set as the onset of each participant's first foot stamp on the deck of the surfboard. For the muscle activation data, the resultant accelerations recorded by the accelerometers housed in the surface electromyography sensors that were placed over the tibialis anterior muscle for the lead and trail limbs were calculated to facilitate alignment of the data sources. Plots, which displayed the foot stamp impacts generated by each participant, were then generated for each data source. These stamp impact plots were then manually aligned so that the MATLAB script could automatically detect the aerial landing impact and export processed datasets for further analysis. Initial contact (IC) between the participant on the surfboard and the landing mat was determined as the time at which the force generated on the surfboard deck exceeded a threshold of 50 N for a minimum of 50 ms. The trail limb foot contact latency (ms), peak vertical forces (N), time-to-peak (s), and loading rates (N/s) generated during the landing phase of each FA and FAR trial were then calculated, with the non-temporal data normalized relative to each participant's body mass. As the lead and trail limbs often landed at different times, the time-to-peak force and loading rate variables were calculated relative to the IC of each limb.

Muscle Activation Patterns. Surface electromyography (sEMG) sensors (Trigno IM sensors; 27 × 37 x 15 mm, mass <15 g each; Delsys Inc., USA) were adhered bilaterally over the muscle bellies of tibialis anterior (TA), medial gastrocnemius (MG), vastus medialis (VM), rectus femoris (RF), biceps

Figure 1. The airborne phase of the Frontside Air Reverse (FAR) where the participant, who has a natural surfing stance (left foot forward), places his feet on the surfboard in preparation for landing whilst rotating approximately 180° in the air.

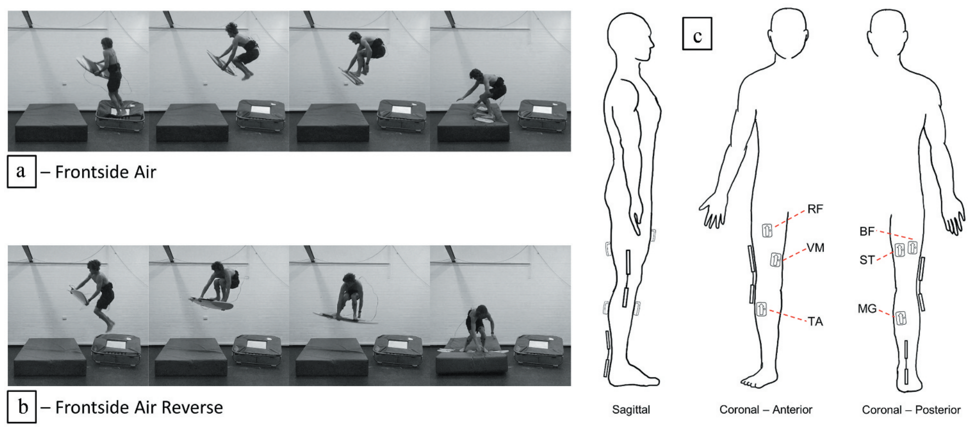

Figure 2. Sequences of the (A) Frontside Air and (B) Frontside Air Reverse, along with (C) a schematic of the equipment set-up on the participants from three different views. TA = tibialis anterior, MG = medial gastrocnemius, VM = vastus medialis, RF = rectus femoris, BF = biceps femoris, ST = semitendinosus.

femoris (BF), and semitendinosus (ST) for each participant, following the SENIAM guidelines (see Figure 2; Hermens et al., 2000). These muscles were selected due to their role in controlling the ankle and knee joints during landing, as well as being suitable for capturing sEMG data. The raw sEMG signals for each muscle during the FA and FAR trials were then digitally recorded (1111 Hz; 50–450 Hz bandwidth) using a Trigno™ 16-channel system (Delsys Inc., USA). The sEMG signals were exported for analysis using a custom MATLAB script. Raw data were first visually inspected to eliminate any trials that were obviously contaminated with noise and then resampled to 1000 Hz for analysis. The resampled signals were full-wave rectified and filtered with a 14 Hz 4th-order, zero-lag low-pass Butterworth filter to create a series of linear envelopes to determine the recruitment patterns of the muscle bursts involved in the landing phase of the aerial manoeuvres. Muscle onset was deemed to have occurred when the amplitude of the sEMG signal exceeded a threshold of five times the standard deviation of the baseline activation (measured across 200 samples) and remained above this level for more than 50 ms during the event window. Muscle offset was deemed to be the time point at which the sEMG amplitude returned to baseline, below the aforementioned threshold. The primary investigator (J.R.F.) manually inspected all muscle onsets and offsets relative to the original sEMG traces and manually adjusted any temporal characteristics where necessary. The time of peak muscle activation (ms) was also captured and muscle burst duration (ms) was calculated based on the muscle burst onset and offset times.

Ankle and Knee Joint Kinematics. Wireless electronic goniometers (226–326 x 22 × 12 mm, mass = 25–29 g; 1000 Hz; Biometrics Pty Ltd, UK) were placed over the lead and trail joints of the ankles (W110) and knees (W150) to monitor lower limb motion during the aerial tasks. Contact switches (FS4; Biometrics Pty Ltd, UK) were taped to the plantar surface of the ball and heel of the participants' feet to assist in later time synchronizing the three data sources. The kinematic data were analysed using the custom MATLAB script described previously. Once the goniometric data had been time synchronized to the force and sEMG data, the data were filtered using a 4th-order low-pass Butterworth filter (f_c = 20 Hz). Joint angles for the ankle and knee of the participants' lead and trail limbs were then sampled at the time of IC (°), the time of the minimum joint angle ($DISP_{min}$; °), and the time of the peak joint angle ($DISP_{peak}$; °). From these time points, total joint displacement ($DISP_{ROM}$; °), the duration of displacement ($DISP_{dur}$; s), and the average joint velocity ($DISP_{vel}$; °/s) were calculated.

Statistical analysis

With the high number of dependent variables tested in this study, rather than using the average of the five trials performed for each aerial variation, each trial was treated as independent (n = 306) to ensure there were sufficient observations to meet the assumptions underlying the statistical tests. Because each participant completed approximately five trials,[1] behaviour from any individual trial was not expected to skew the results of the analysis. Following the removal of any extreme outliers (>3 standard deviations above the mean), the mean and standard deviation of the dependent kinetic, kinematic, and muscle activation variables were calculated to describe each participant's performance. Principal component analysis (PCA) was employed to reduce the 41 variables to 10 latent variables. Visual inspection of the scree plot showed that 10 components was the optimal number, supported by only those variables with an eigenvalue >1, resulting in the total variance explained of 79.8%. Factor scores were calculated for each variable ($r > 0.35$; see Supplementary Figure S1 and Supplementary Table S1) and a two-way MANOVA analysis was used with limb (lead, trail), aerial variation (FA, FAR), and the interaction of limb and aerial variation as fixed effects. Univariate analysis of variance (ANOVA) was then used to identify the factor(s) that showed significant differences. All statistical tests were performed in R (version 4.0.2; Vienna, Austria).

[1]In some occasions, more than five trials were collected to ensure that the participant's feet were in contact with the surfboard before landing. These trials were included in the analysis because there was no expectation that a single trial would substantially influence the outcome of any statistical testing.

Results

When performing the FA and FAR, the participants jumped upward approximately 1.39 ± 0.20 m and 1.41 ± 0.18 m (p = 0.352), respectively, before contacting the landing mat. Of 102 FA attempts, the participants successfully landed 76 (74.5%). Similarly, when attempting the FAR participants landed 77 of 103 trials (74.8%). Only data from successful FA and FAR attempts were included in the biomechanical analysis described below. When landing these different variations, the additional rotation required when performing the FAR resulted in a trail limb contact latency of 32 ± 23 ms, whereas the contact latency of the trail limb for the FA was only 4 ± 11 ms. Descriptive statistics for the forces generated at landing are presented in Table 1. Force

Table 1. Kinetic variables for the lead and trail limb during the Frontside Air and Frontside Air Reverse.

	Simulated Aerial Task Variation			
	Frontside Air		Frontside Air Reverse	
	Lead Limb	Trail Limb	Lead Limb	Trail Limb
Peak Force (N)	1079.1 ± 262.5	1043.2 ± 202.5	982.1 ± 263.1	1134.1 ± 351.3
Peak Force (BW)	1.56 ± 0.28	1.52 ± 0.24	1.40 ± 0.31	1.64 ± 0.35
Time to Peak Force (s)	0.032 ± 0.019	0.024 ± 0.014	0.053 ± 0.036	0.035 ± 0.035
Loading Rate (N/s) *‡	42,385.0 ± 26,162.1	59,113.3 ± 43,640.2	28,500.4 ± 22,891.3	47,565.4 ± 39,291.2
Loading Rate (BW/s) *‡	62.6 ± 38.5	91.7 ± 77.7	40.2 ± 30.0	67.9 ± 53.7

* denotes significant difference between aerial variations (p < 0.05)
‡denotes significant difference between lead and trail limbs (p < 0.05)

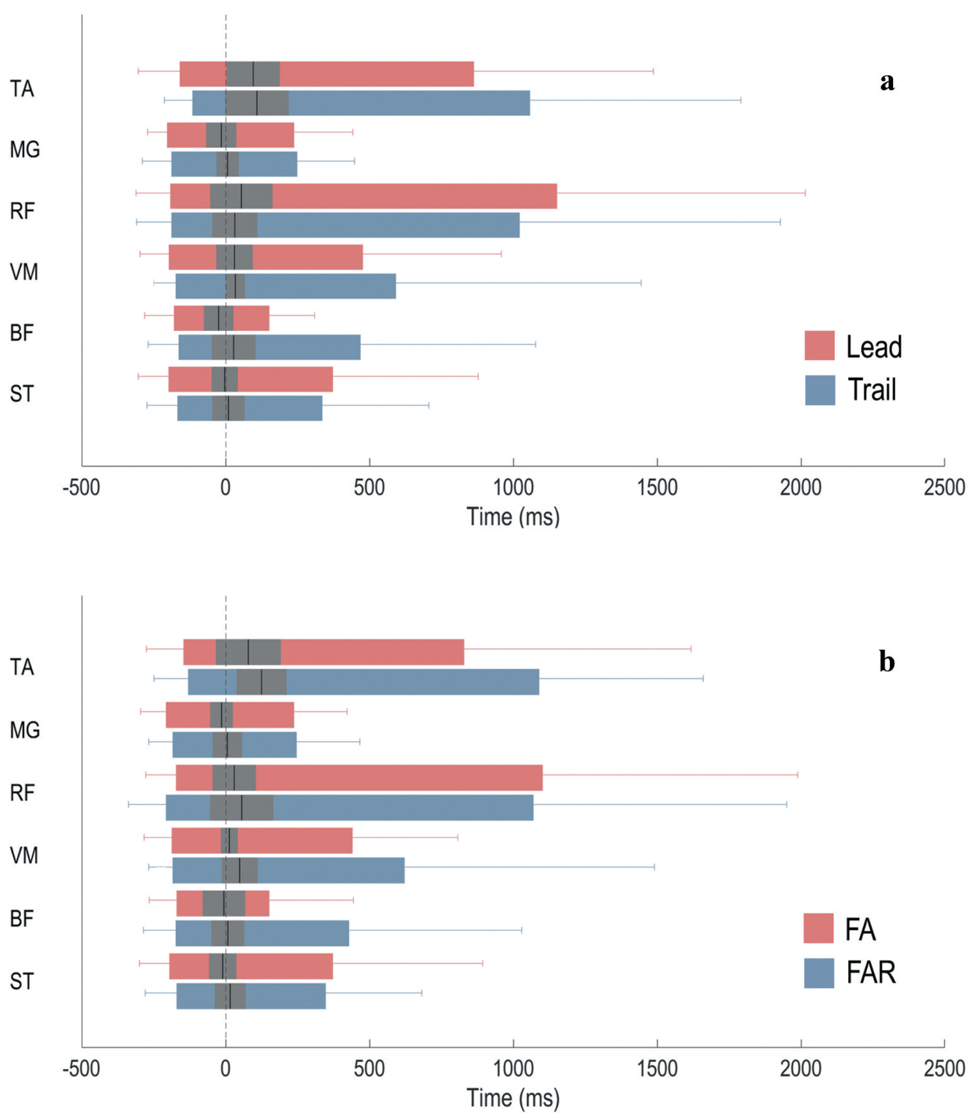

Figure 3. The timing of muscle burst onset, peak and offset for (A) each limb and (B) each aerial variation. Each time point has the standard deviation (SD) represented by error bars (onset, offset) or shading (peak). FA = Frontside Air, FAR = Frontside Air Reverse.

Table 2. Kinematics of the ankle and knee during the landing event of two simulated aerial task variations.

	Kinematic Variables					
	IC (°)	$DISP_{min}$ (°)	$DISP_{peak}$ (°)	$DISP_{ROM}$ (°)	$DISP_{dur}$ (s)	$DISP_{vel}$ (°/s)
Frontside Air						
L Ankle *DF*	1.3 ± 4.2	0.8 ± 4.2	9.9 ± 4.5	9.2 ± 4.6	0.94 ± 0.79	17.0 ± 23.5
T Ankle *DF*	1.1 ± 3.4	0.4 ± 3.5	11.0 ± 4.5	10.7 ± 5.0	1.19 ± 1.10	19.4 ± 21.1
L Knee *F*	42.7 ± 10.4	35.3 ± 9.5	96.3 ± 19.5	60.7 ± 17.3	0.48 ± 0.52	181.1 ± 76.4
T Knee *F*	42.7 ± 12.1	36.6 ± 8.5	106.9 ± 19.4	70.2 ± 18.5	0.57 ± 0.66	195.2 ± 101.2
Frontside Air Reverse						
L Ankle *DF*	3.8 ± 40	3.3 ± 4.1	10.9 ± 5.0	7.6 ± 3.5	0.43 ± 076	60.6 ± 52.6
T Ankle *DF*	2.5 ± 3.3	1.0 ± 2.8	11.5 ± 5.0	10.5 ± 4.7	0.95 ± 1.08	32.6 ± 39.3
L Knee *F*	52.2 ± 14.8	37.7 ± 8.7	90.8 ± 16.8	53.9 ± 17.6	0.54 ± 0.53	154.5 ± 86.1
T Knee *F*	47.3 ± 15.5	33.0 ± 7.6	101.2 ± 22.5	68.3 ± 19.7	0.87 ± 0.90	140.8 ± 89.9

L: Lead, T: Trail, DF: Dorsiflexion, F: Flexion, IC: Initial Contact, $DISP_{min}$: Joint Displacement Minimum Angle, $DISP_{peak}$: Joint Displacement Peak Angle, $DISP_{ROM}$: Joint Displacement Range of Motion, $DISP_{dur}$: Joint Displacement Duration, $DISP_{vel}$: Joint Displacement Average Velocity.

data for one participant could not be captured due to technical issues. Additionally, mean ± standard deviation values for the muscle onset, offsets, peaks and durations, and for the kinematic variables are presented in Figure 3 and Table 2, respectively.

Aerial variation and limb interaction

There was no significant interaction between the type of aerial variation (FA, FAR) and the landing limb (lead, trail) for any of the variables ($F_{(10,293)}$ = 0.7617, p = 0.666, Wilks' Λ = 0.975). Therefore, any significant main effects of landing limb were not dependent upon the type of aerial performed.

Main effect of limb

There was a significant main effect of limb on the combined dependent variables ($F_{(10,294)}$ = 2.7382, p = 0.003, Wilks' Λ = 0.915). Follow-up univariate ANOVAs on the 10 rotated components identified that there was a significant difference between limbs in the rotated component 10 (RC10) ($F_{(1,303)}$ = 20.660, p < 0.0001, η^2 = 0.064). That is, the surfers generated a significantly lower loading rate, both in Newtons and when normalized to BW, when landing on the lead limb compared to when landing on the trail limb (between limb difference = −18,150.4 N/s and −28.8 BW/s).

Main effect of aerial variation

There was also a significant main effect of aerial variation on the combined dependent variables ($F_{(10,294)}$ = 4.2231, p < 0.0001, Wilks' Λ = 0.874). Follow-up univariate ANOVAs on the 10 rotated components identified that there was a significant difference between the two aerial variations in the same rotated component, RC10 ($F_{(1,303)}$ = 31.655, p < 0.0001, η^2 = 0.095). That is, when landing the FA, the surfers generated a loading rate that was 13,050.1 N/s and 23.6 BW/s higher than when landing the FAR.

Discussion

Aerial manoeuvres have become one of the most effective ways a surfer can potentially increase his or her single-wave score during a surfing competition. The radical way surfers perform these aerial manoeuvres, both recreationally and in competition, however, has resulted in a growing incidence of acute lower limb injuries, particularly ankle and knee injuries (Furness et al., 2015; Hohn et al., 2020; Inada et al., 2018; Lundgren, Butel et al., 2014; Minghelli et al., 2018; Nathanson et al., 2007). The current study is the first to investigate how surfers perform two variations of a simulated aerial task, including the forces generated at landing and the muscle activation patterns controlling the ankle and knee joint motion during this critical phase of each task. Our results revealed that there are significant differences in how participants dissipate the forces generated at landing when performing both the FA and the FAR, and that the surfers' lead and trail limbs play unique roles in attenuating these impact forces. The implications of these novel findings are discussed below.

Although there was no significant limb x aerial variation interaction, there was a significant main effect of limb on RC10, such that the rate of loading when landing, both absolute and relative, was significantly higher for the trail limb relative to the lead limb, irrespective of the aerial variation the surfers performed. When performing both the FA and FAR, the participants tended to land with the lead limb contacting the surfboard first, with the trail limb contacting the surfboard 4 to 32 ms later. Close inspection of the video images of each trial revealed that the surfers appeared to initially control their lead limb while landing, possibly to ensure it was in position to dissipate the forces generated at initial contact. In contrast, the subsequent contact of the trail limb was less controlled and tended to "slap" down on the surfboard, resulting in a higher loading rate. This finding is important due to the high proportion of injuries that occur to the trail limb ankle and knee in surfing (Hohn et al., 2020). Repeated landings with a high loading rate have been suggested to increase the likelihood of both acute and overuse injuries in land-based sport athletes (Bisseling et al., 2008; De Bleecker et al., 2020; Dufek & Bates, 1991). We speculate that repetitive landings where the trail limb must attenuate the high rates of loading at board-wave contact may increase the likelihood of a surfer sustaining an acute injury, such as an MCL injury when this high rate of loading is combined with pronounced knee valgus. Dynamic knee valgus, or the "knocked knee" position, of the trail limb is commonly adopted by surfers performing turning and aerial manoeuvres (Forsyth et al., 2018; Hohn et al., 2020), often due to its perceived aesthetic benefit. Developing a more controlled placement of the trail limb rather than allowing it to "slap" down on the surfboard could be one strategy to decrease the rate of loading of this limb when surfers attempt to land aerial manoeuvres, although this notion warrants further investigation.

Similar to the main effect of limb, the only rotated component extracted from the PCA to have a significant main effect of aerial variation was RC10, which related to the rate of loading. That is, although there was no significant difference in the forces generated at landing between the FA and FAR (p = 0.688), there were large differences between the two tasks in both the absolute and relative loading rate. The lower rates of loading evident during the FAR are likely to be explained by the additional rotation while in the air required in the FAR relative to the FA. In an attempt to arrest this rotation upon landing, each participant tended to "roll" from the nose to the tail of the surfboard while landing, increasing the time over which to dissipate the forces. When performing a FAR in the ocean, surfers land FAR manoeuvres in reverse and shift their mass towards the centre of the surfboard to keep the tail of the surfboard from submerging (Forsyth et al., 2018, 2020b). This more sequential landing strategy may also increase the time that a surfer has to attenuate the forces generated at landing, thus decreasing the rate of loading due to the impulse–momentum relationship (Devita & Skelly, 1992). Conversely, when landing the FA the participants appear to have simply braced for impact, unable to move through a substantial range of motion in either the ankle or the knee (see Table 2). It is possible that during both tasks there is a high level of lower limb muscle co-contraction to account for this reduced range of motion and to allow greater adaptability to perturbations (Russell et al., 2007). The lack of rotation and subsequent "roll", however, results in a simultaneous, stiffer landing, thereby increasing the rate of loading. Although the results of the present study highlight some important differences in the rate of loading experienced by surfers performing simulated aerial landings, it is essential that future research verifies the loads and rates of loading surfers experience when performing aerial manoeuvres in the ocean.

In contrast to our hypothesis, there was no significant limb x aerial variation interaction for any of the rotated components of the PCA, suggesting that there was no relationship between the combined variables for the two tasks and two limbs. This finding was not expected because the FA and FAR have substantially different airborne phases (without and with rotation) and previous research has suggested that surfers use the lead and trail limb differently when performing these two aerial variations (Forsyth et al., 2018, 2020b). Furthermore, there were no significant main effects of either the limb or aerial variation on the joint kinematics the surfers displayed during landing or how they activated their lower limb muscles in preparation to land. We speculate that this lack of interaction between limb and aerial variation and lack of difference in landing technique is due to the basic feedforward response necessary to prepare and position the lower limbs before landing (Santello, 2005; Santello & McDonagh, 1998; Santello et al., 2001; Whitting et al., 2007). There is a substantial body of research that documents that the technique an individual will use to land will depend on the impact forces he or she anticipates at foot-ground contact (James et al., 2003; Lesinski et al., 2017; Liebermann & Hoffman, 2005; Santello, 2005; Santello & McDonagh, 1998; Santello et al., 2001; Steele & Milburn, 1988; Whitting et al., 2007). Factors such as variations in fall heights and descent velocity immediately prior to landing, which will affect the ground reaction forces generated at landing, can therefore affect landing technique (Lesinski et al., 2017; Santello & McDonagh, 1998; Santello et al., 2001; Sidaway et al., 1989; Whitting et al., 2007). Because both simulated aerial variations had the same fall height, the participants are likely to have had equivalent expectations of the landing forces and impact velocities, in turn, using a similar lead and trail limb strategy to land, irrespective of task variation (Santello & McDonagh, 1998; Santello et al., 2001; Sidaway et al., 1989; Whitting et al., 2007). The lack of limb x aerial variation interaction may also be explained by the highly constrained nature of landing a simulated aerial onto a surfboard. That is, the participants had to land on a narrow surfboard and then immediately hold a stabilized landing position on the landing mat, while the landing surface remained consistent across all trials, irrespective of the aerial variation they performed. Such a constrained task is likely to demand a constrained landing strategy. Landing on a moving surfboard in the ocean, however, is unlikely to be as constrained. It is therefore possible that a surfer might need to adjust his or her preparation when landing on different sections of a wave, such as the turbulent white water of a broken wave, or the unbroken "flats" in front of the breaking wave. This notion is supported by previous research which has shown that when landing on an unstable surface participants displayed significantly lower normalized muscle activity during the preactivation phase of a drop landing compared to when landing on a stable surface (Prieske et al., 2013). Future research is therefore recommended to see whether this relationship (or lack thereof) occurs when surfers perform a FA and FAR in the ocean or a wave pool.

Although the present study provides insightful data about the temporal patterns of the lower limb muscles, this does not include information about the magnitude of these contractions or how these may differ between limbs and/or variations. We suggest that future studies look at the amplitude of muscular contraction prior to and following landing to evaluate how this may influence a surfer's capacity to dissipate the forces generated at landing, as well as investigate the magnitude of co-contraction present during these tasks, as this may explain some of our results. Furthermore, we only collected data while the participants performed simulated aerials in a laboratory environment and not while performing aerials in the ocean. Due to the highly constrained nature of this simulated task, there might be differences in how surfers coordinate their lower limbs to dissipate the forces generated when landing aerials in the ocean. It is also acknowledged that trunk and upper limb motion will contribute to how surfers perform aerials and so further research to examine whole body motion during aerial execution is encouraged.

Conclusion

When performing simulated aerial manoeuvres, surfers generated significantly higher loading rates when landing on the trail limb compared to the lead limb, irrespective of aerial variation. We speculate these higher loading rates are due to the tendency for surfers to "slap" the trail limb down when landing, rather than using a more controlled placement of the limb. The surfers also generated higher loading rates when performing the FA compared to the FAR, whereby the additional rotation prior to landing during the FAR appeared to allow the surfers to "roll" through the landing, increasing the time over which they could dissipate the landing forces. Practitioners are encouraged to consider the demands that these manoeuvres may place on the lower limb, particularly the trail limb, when designing dry-land training. Additionally, future research is recommended to verify whether these loading strategies are replicated when surfers perform aerial manoeuvres in the ocean, and whether high loading rates are associated with lower limb injuries in surfing, particularly injuries to the trail limb.

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Disclosure statement

James R. Forsyth, Christopher J. Richards, Ming-Chang Tsai, John W. Whitting, Diane L. Riddiford-Harland, Jeremy M. Sheppard and Julie R. Steele declare that they have no conflicts of interest relevant to the content of this review.

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