

RELATION BETWEEN MAXIMUM PLANTAR PRESSURE DISTRIBUTION AND CLUBHEAD SPEED IN AMATEUR GOLFERS

Todd C. Pataky

Department of Bioengineering, Shinshu University, Ueda, Japan

Disagreements exist regarding the manner in which weight should be dynamically shared both within- and between-feet to generate maximal golf clubhead speed. The purpose of this study was to test the null hypothesis that maximum plantar pressure (PP) distributions do not correlate with clubhead speed. Thirty-two amateur golfers (handicaps: 2.7-25) performed 10 swings with a driver. Clubhead speed was measured using a ball-flight monitor and PP distributions were recorded using an insole system. Results showed a significant positive correlation between lateral forefoot PP and clubhead speed ($p=0.024$) in the target-foot (the foot closest to the target), and this effect was independent of body mass ($p=0.039$). In contrast, medial PP tended to be *negatively* correlated with clubhead speed. This suggests that target-foot loading *location* may be as important as loading itself for maximizing clubhead speed.

KEY WORDS: foot, biomechanics, golf, force distribution, random field theory.

INTRODUCTION: Since foot-ground interface forces determine the acceleration of the body's center of mass, it is reasonable to presume that stereotypical foot forces are required to optimally drive golf swing kinematics. It has been postulated that force sharing between the 'target' and 'back' feet (Fig.1a), as manifested in parameters such as the center of pressure (COP), can differentiate amongst golfing skill levels (Richards et al. 1985), and in particular that highly skilled golfers exhibit greater COP_y (i.e. target-direction) excursion than less-skilled golfers.

However, the manner in which golfers dynamically distribute forces across the back- and target-feet is less clear. One could, for example, start with a loaded back-foot heel and then finish with loaded target-foot toes, and this would achieve the same COP_y excursion as starting with the toes and finishing with the heel. It could be argued that these two extremes differentially constrain swing path and ball contact possibilities. Of only the few existing studies that could distinguish amongst these possibilities, one suggests that the target foot heel should be loaded through ball contact (Richards et al. 1985), and another supports this anecdotally through observations that 'target foot golfers', who have a more posterior COP_x through ball impact, have lower average handicaps (Ball and Best 2011). Somewhat contradictory to these findings are observations from a third study that both heel and hallux forces, but not lateral forces, are associated with golf skill (Kawashima et al. 1998).

A limitation of these studies is that neither clubhead speed nor skill level was treated as a continuous variable. This is problematic, not only because terms like "high skill" and "low handicap" are imprecisely defined, thereby making it difficult to resolve inter-study differences, but more importantly because a categorical comparison of clubhead speed (or skill-level) groups is inherently a weaker statistical design than (continuous) regression analysis.

The purpose of this study was to examine the correlation between spatially continuous foot force distributions and clubhead speed, a variable highly correlated with golf skill (Fradkin et al. 2004), in amateur golfers in attempts to resolve discrepancies in published descriptions of foot-loading solutions in high- vs. low-skill golfers. To this end, the following null hypothesis was tested: *maximum in-shoe plantar pressure distributions occurring during the golf swing do not correlate with clubhead speed.*

METHODS: Thirty-two male amateur golfers (age: 45.2 ±13.1 years, height: 176.2 ±6.0 cm, mass: 76.4 ±7.7 kg) provided informed consent to participate in this experiment. Their self-reported handicaps ranged from 2.7 to 25. Each subject was fitted with the same model of

golf shoe (Nike Lunarlon Control) and then each hit 10 driver shots on artificial turf after warming up with 10-20 practice swings. Clubhead speed was recorded with a Flightscope X2 Doppler radar launch monitor (EDH Ltd., Stellenbosch, South Africa). In-shoe plantar foot pressures were recorded at 100 Hz using a Pedar X system (Novel GmbH, Munich, Germany). For each swing the maximum pressure distribution was extracted from the two-second window centered on the instant of maximum target-foot ground reaction force (GRF); GRF was estimated from as the sum of instantaneous sensor forces.

Linear regression was used to evaluate the relation between maximal pressure distributions and clubhead speed. Within-subject regressions were presently found to be non-significant in all subjects (see Discussion), so only between-subject analyses are presently described. First the mean clubhead speed and mean pressure distribution were computed for each subject. The pressure values were then regressed against clubhead speed, separately for each sensor, yielding one correlation coefficient (r) per sensor and thus resulting in one r distribution per participant. This r distribution was converted to a t statistic distribution using the identity:

$$t = r\sqrt{(n-2)/(1-r^2)}$$

where n is the number of subjects ($n=32$) and where t has the Student's t distribution with $(n-2)$ degrees of freedom. The significance of the t distributions was assessed using random field theory (RFT) (Pataky 2008). In particular, the spatial smoothness of the pressure data, as estimated from the average spatial pressure gradient of the regression residuals, was used to determine the t threshold that only $\alpha=5\%$ of sensors would exceed if the pressure distributions resulted from a completely random process with identical smoothness.

RESULTS: The cross-subject average distribution (Fig.1a) exhibited high pressures over the lateral and posterior target-foot and also over the target-foot hallux. High pressures were also observed over the hallux and medial forefoot in the back foot. The linear regression between clubhead speed and pressure was found to be significant at certain single sensors (Fig.1b).

Expanding regression analysis to the whole target-foot (Fig.1c) revealed that pressures over the bulk of the target-foot were positively correlated with clubhead speed, except for the medial midfoot and posterior heel, where pressures tended to be negatively correlated with clubhead speed. Statistical inference confirmed a significant positive correlation at the lateral forefoot ($p=0.024$) (Fig.1d). An additional isolated sensor at the lateral midfoot also exceeded the critical t threshold, but not the p threshold ($p>0.05$).

In contrast, the bulk of the back-foot pressures tended to be negatively correlated with clubhead speed (Fig.1c). Only the very anterior foot tended to exhibit positive correlation. These back-foot tendencies failed to reach significance. Using body mass as a covariate did not alter any of the aforementioned results (Fig.1e,f), suggesting that the present results are robust to a wide range of body masses.

DISCUSSION: The presently observed positive correlations between maximum target-foot pressures and clubhead speed (Fig.1c) supports the conventional wisdom that 'weight transfer' to the target-foot is important for generating clubhead speed, and it also agrees with the invariant

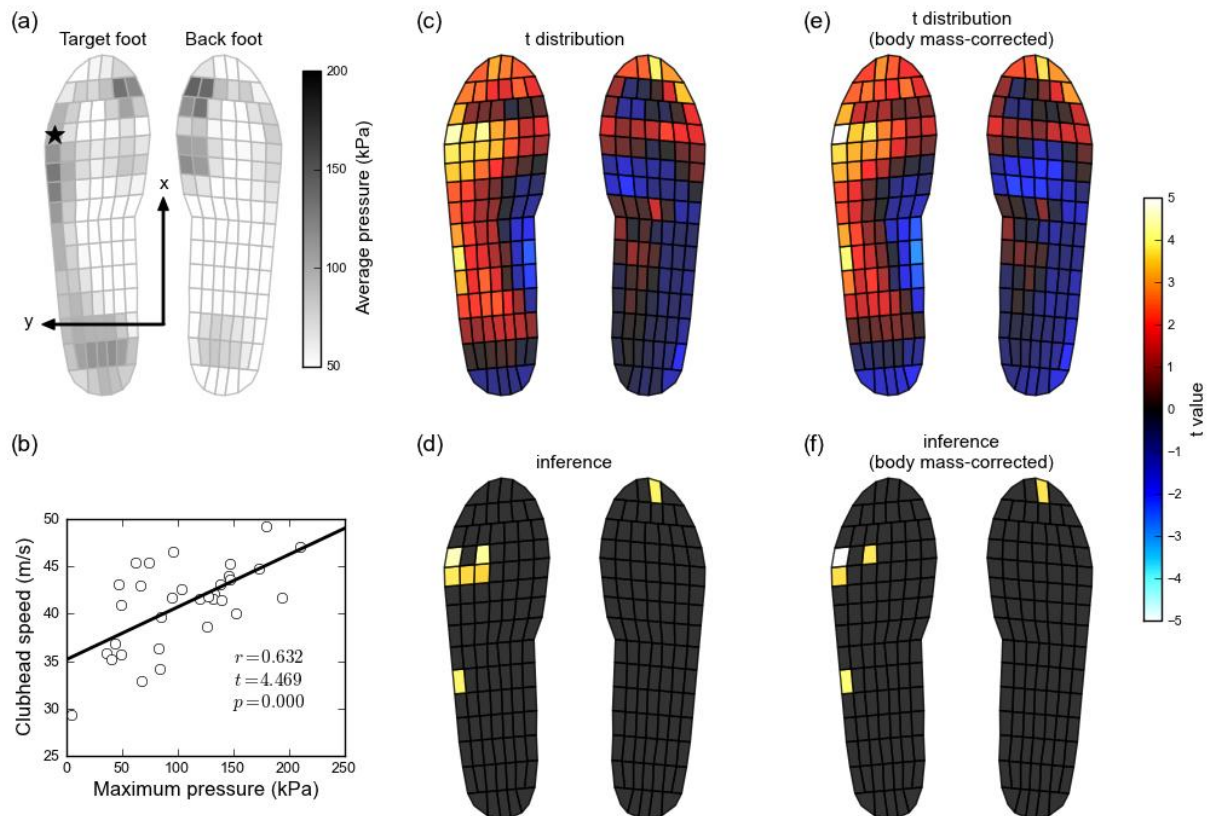


Figure 1: Linear regression results. (a) Average pressure distribution across (right-handed) participants, with a point of interest (POI) indicated at the location of maximum positive correlation. (b) Clubhead speed vs. average POI pressures for each participant. (c) Distribution of the t statistic for all sensors. (d) Statistical inference ($\alpha=0.05$, critical $t=3.58$). (e,f) Body mass-corrected results (i.e. mass as a covariate of no empirical interest).

scientific findings of increased target-foot loading in skilled vs. unskilled golfers (Richards et al. 1985; Okuda et al. 2010). This increased loading was presently observed to occur predominantly at the lateral forefoot (Fig.3c,e), and while previous results also show or imply increased target-foot loading in skilled vs. unskilled golfers (Kawashima et al. 1998), the present results are the first to demonstrate significant correlation between clubhead speed and the pressure distribution itself. Importantly, these pressure distribution results suggest that loading location may be as important as foot loading itself. In particular, loading arbitrary target-foot locations, especially the mid- and posterior back-foot, may be counterproductive (Fig.1c,e).

This target-foot lateral midfoot finding is somewhat contradictory to a report of no COPx position differences between <3 and 10-18 handicap golfers (Healy 2009). However, golfers in the cited study were tested barefoot on a pressure mat, which likely reduced both foot stability and foot-ground friction with respect to shod golf swings. The present results also disagree with both (i) findings that higher target-foot hallux loads in skilled golfers with an average handicap of 5.5 (Kawashima et al. 1998), and (ii) findings that medial forefoot target-foot pressures are associated with the longest drives (Wallace et al. 1994) within a handicap range of 5-10.

However, given that different handicaps are associated with different clubhead speeds (Fradkin 2004), it is conceivable that the present result reflects a trend in competent (mid-handicap) amateur golfers, and that the results of all studies would converge if the handicap and clubhead speed ranges were more similar.

From a mechanical perspective the anterior-posterior location of target-foot loading is potentially important because it partially reflects the pivot point about which the swing occurs.

It is conceivable that varying the location of the pivot point along the X direction (Fig.1a) alters clubhead path, and thus target-direction clubhead speed. However, this is purely speculative, and 3D dynamic analyses would be necessary to elucidate such a mechanism.

Although within-subject analyses failed to reach significance (not presented in interest of space) the present subjects were tested only in a single bout of ten swings. Clubhead speed could likely improve non-trivially through altered swing mechanics, at which point the present null hypothesis could be re-tested. That is, a lack of within-participant correlation does not preclude the possibility that ideal swing mechanics involve lateral forefoot target-foot loading. Additionally, since golf-swing performance determinants have been shown to vary substantially from participant-to-participant [3], it is possible that additional and potentially more sophisticated regression analyses, tailored to each individual, could elucidate within-participant effects.

The present analyses were limited to maximum pressure distributions and thus failed to consider temporal events (e.g. start of the downswing, ball impact). Since timing effects are an important marker of skill level (Richards et al. 1985) it is likely that instantaneous pressure distributions may further elucidate clubhead speed-relevant trends.

CONCLUSION: This study found significant positive correlation between clubhead speed and lateral forefoot pressures in the target foot, and failed to find significance elsewhere, in either foot. This suggests that target-foot loading location may be as important as target-foot loading itself for maximizing clubhead speed. It may be beneficial for coaches to monitor PP distributions to ensure that weight is transferred to appropriate foot locations.

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