OneStep

WHITE PAPER · GAIT KINETICS

A New Kinetic Parameter: Maximum Heel Strike Force

Measuring ground reaction force at heel strike with a smartphone in the pocket

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A New Kinetic Parameter: Maximum Heel Strike Force

Validation, normative range and clinical behavior of a smartphone-derived measure of ground reaction force

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ABSTRACT

Background. Smartphone gait analysis has so far focused on spatiotemporal parameters. Gait kinetics, the forces exerted on the body by the ground, offer a complementary view of gait health but have traditionally required instrumented walkways or force plates.

Objective. To introduce and validate OneStep's first kinetic parameter, maximum heel strike force, measured with a single smartphone carried in the trouser pocket during walking.

Methods. Maximum heel strike force was defined as the peak ground reaction force during the heel strike phase, normalized to body weight. Validity was assessed against a pressure-sensitive treadmill (Motek C-Mill) in 32 subjects, 10 with healthy gait walking at several speeds and simulating pathological patterns, and 22 with pathological gait, using intraclass correlation coefficients ($ICC_{3,1}$). The normative distribution was characterized in 783 patients from skilled nursing, surgical recovery and outpatient and remote-monitoring settings. Behavior during recovery and across populations was examined descriptively.

Results. Agreement with the reference system was good, with $ICC_{3,1}$ of 0.870 for primary and 0.869 for secondary heel strike. Across 783 patients the mean normalized force was 1.31 (range 0.90–1.87; 10th–90th percentile 1.10–1.52). The parameter changed markedly over recovery from total joint replacement, in step with cadence, double support and stride length, and showed distinct values between patients and populations at the same walking speed.

Conclusions. Maximum heel strike force can be measured reliably from a pocketed smartphone and adds a kinetic dimension to gait assessment. It is the first step toward measuring gait kinetics with OneStep's technology.

KEY POINTS

Question	Can a kinetic gait parameter, the peak ground reaction force at heel strike, be measured with a smartphone in the pocket?
Findings	Against a pressure-sensitive treadmill in 32 subjects, agreement was good (ICC 0.87). In 783 patients the normalized force averaged 1.31 body weights (10th–90th percentile 1.10–1.52), and it tracked recovery after joint replacement.
Meaning	Smartphone gait analysis can extend beyond spatiotemporal measures into kinetics, giving clinicians another lens on gait health and recovery.

KEYWORDS gait kinetics · ground reaction force · heel strike · smartphone · validation · normative values · joint replacement recovery

1 Introduction

Gait can be described in a variety of ways, each giving different clinical insight into the health of a person's walk. To date, OneStep's gait analysis has focused on spatiotemporal parameters: those describing the spatial aspects of gait, such as distance covered, base width and left and right step length, and those describing its temporal aspects, such as the share of time spent with both feet on the ground or the number of steps per minute.

Spatiotemporal parameters provide deep insight into a patient's walk, but other measurements offer a different view. One particularly powerful approach is gait

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kinetics, the forces exerted on the body by the ground during walking. Kinetic parameters include moments and forces at various points in the gait cycle, as well as the location and variance of the center of pressure on the ground.

Here we present OneStep's first kinetic parameter, maximum heel strike force, which can be measured with a single smartphone carried in the trouser pocket while walking. We report its agreement with a gold-standard system in internal validation, its distribution in a large clinical population, and its behavior during recovery and across clinical populations.

2 Definition of the parameter

Throughout the gait cycle, the ground reaction force, the force exerted on the body by the ground, follows a repeatable pattern over time (Figure 1). In normal gait its maximum occurs during the heel strike phase. Maximum heel strike force is defined as this peak. Its level, normalized by the weight of the walker, provides insight into the health of the walk: whether the patient is stepping too cautiously, with too much force, or within a healthy range.

The raw force is normalized by the patient's weight; otherwise the measurement would be dominated by body weight rather than by the characteristics of gait, a standard practice in gait kinetics.[1] It is further normalized by the acceleration of gravity, so the reported value is a fraction of body weight: a value of 1 represents a force exactly equal to the person's weight.

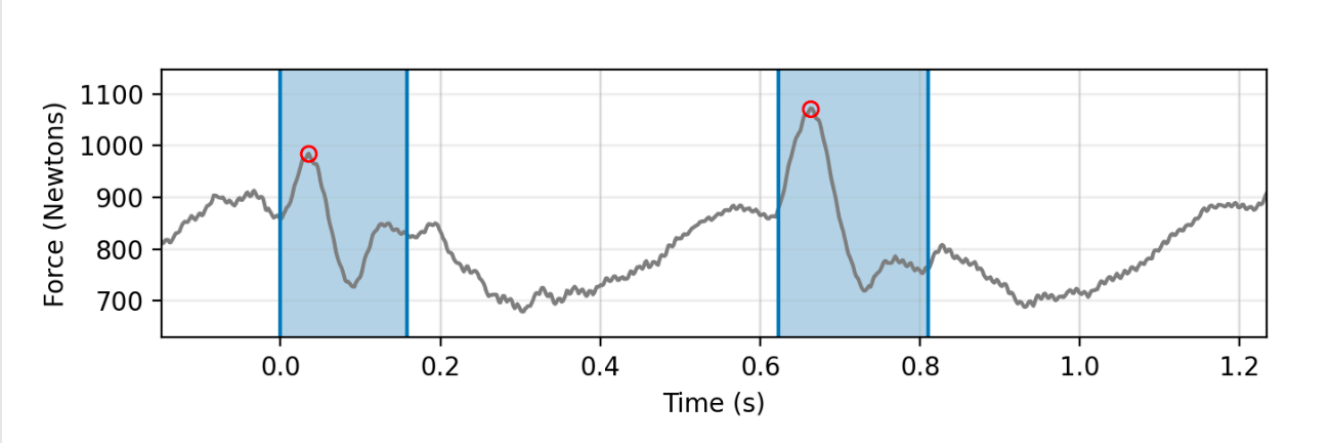


Figure 1. Ground reaction force during gait. The force applied by the ground on the body during a normal gait cycle follows a repeatable pattern over time. Blue-shaded regions mark the interval from heel strike of one foot to toe-off of the opposite foot; red circles mark the moment of maximum force.

3 Methods

3.1 Validation against a reference system

OneStep's measurement of maximum heel strike force was compared with a gold-standard gait measurement system, the Motek™ C-Mill pressure-sensitive treadmill. Measurements were recorded on the treadmill while subjects simultaneously carried two smartphones running the OneStep application, one in each trouser pocket. The validation set comprised 32 subjects: 10 with naturally healthy gait, who walked at several speeds and also simulated a variety of pathological gaits, and 22 patients with pathological gait patterns, who walked with their natural gait. Agreement was quantified with the intraclass correlation coefficient ($ICC_{3,1}$) and Bland–Altman analysis, separately for the primary heel strike (the leg on whose side the phone was carried) and the secondary heel strike (the opposite leg).

3.2 Normative distribution

The distribution of maximum heel strike force was calculated across 783 patients drawn from skilled nursing facilities, surgical recovery, and outpatient therapy and remote therapeutic monitoring programs. Left and right heel strikes were analyzed separately.

3.3 Clinical behavior

The parameter's course during recovery from total joint replacement was examined alongside established spatiotemporal parameters (cadence, double support and stride length) in longitudinal patient data. Its relationship with walking speed was examined across patients and across a skilled nursing and a remote-monitoring population.

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4 Results

4.1 Validity

Agreement with the reference system was good.[2] $ICC_{3,1}$ was 0.870 for the primary heel strike and 0.869 for the secondary heel strike (Supplementary Figure S1). Bland–Altman analysis showed a mean difference between methods close to zero for the primary heel strike (−0.063) and small for the secondary heel strike (0.213), with 95% limits of agreement of approximately ±1.8.

4.2 Normal range

Across 783 patients, the mean normalized maximum heel strike force was 1.31 body weights, with values ranging from 0.90 to 1.87. The 10th and 90th percentiles were 1.10 and 1.52 (Figure 2). Left and right heel strikes followed near-identical distributions. These values provide a reasonable initial approximation of a healthy range for the parameter.

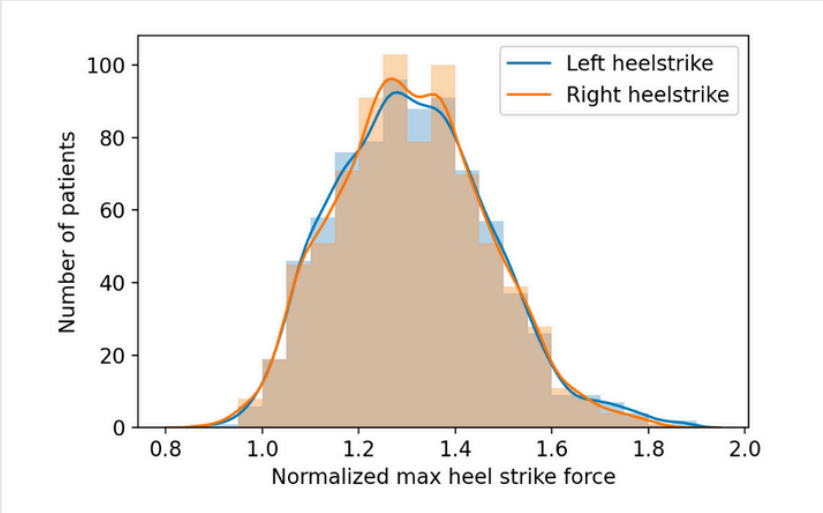


Figure 2. Distribution of normalized maximum heel strike force in 783 patients. Histograms and density curves for left (blue) and right (orange) heel strikes. Force is expressed as a multiple of body weight.

4.3 Behavior during recovery and across populations

Like other gait parameters, maximum heel strike force changed markedly over the course of recovery from total joint replacement (Figure 3). Following surgery it fell sharply and then rose toward its pre-operative level over the subsequent weeks, mirroring the trajectories of cadence, double support and stride length in the same patient.

The parameter was highly correlated with walking speed, yet it showed distinct values between patients, and between populations, at the same walking speed (Supplementary Figures S2 and S3). In this respect it resembles parameters such as double support and stance time, which are strongly related to gait speed at the population level but still carry information about the health of an individual's gait.

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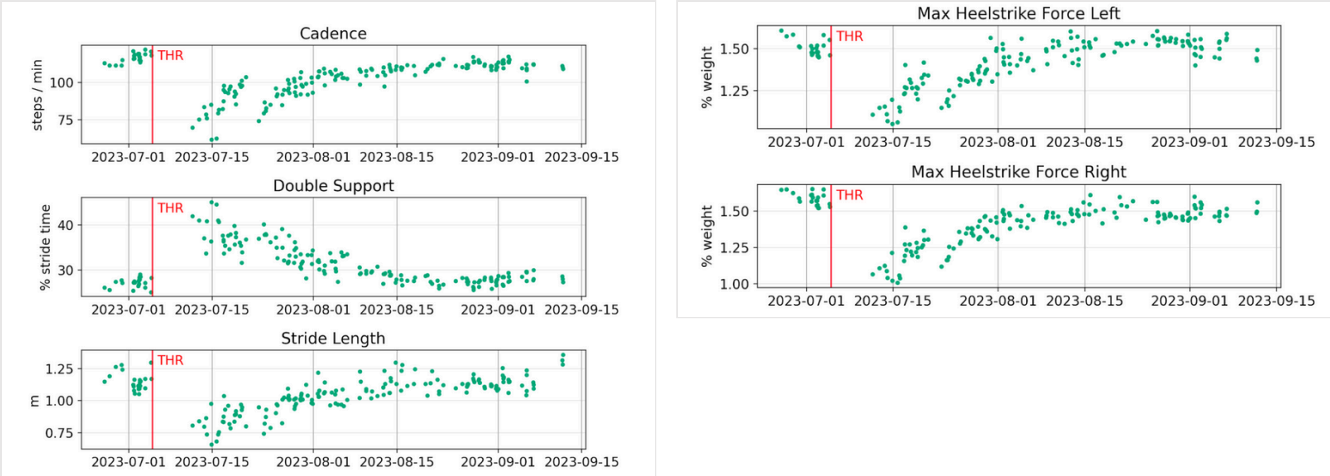


Figure 3. Gait parameters during recovery from total hip replacement. Left: three standard spatiotemporal parameters (cadence, double support, stride length). Right: left and right maximum heel strike force. The vertical red line marks the date of surgery (THR). Recovery is visible in all parameters.

5 Discussion

Maximum heel strike force can be measured from a smartphone in the pocket with good agreement against a pressure-sensitive treadmill, across healthy and pathological gait. Its normative distribution in a large and diverse clinical population provides initial reference values, and its response to surgery and recovery shows that it carries clinically meaningful signal.

The parameter therefore offers clinicians another lens through which to view recovery, and a basis for raising an alert when a patient's heel strike force is not recovering as expected or lies in an unhealthy range. Because it reflects the force a patient commits to each step, it complements spatiotemporal measures: two patients walking at the same speed may load the ground very differently.

5.1 Limitations

Validation was performed on a treadmill in a controlled setting with 32 subjects; agreement during free-living walking was not assessed here. Normative values were derived from clinical populations rather than healthy community-dwelling adults and should be read as initial approximations. The recovery and population comparisons are descriptive.

6 Conclusion

Maximum heel strike force is OneStep's first step into the measurement of kinetic gait parameters using a single smartphone. It is already a useful tool for evaluating patients. Further kinetic parameters will follow, unlocking additional levels of analysis to support treatment, diagnosis and the tracking of progress.

References

1. Winter DA. *The Biomechanics and Motor Control of Human Gait.* Waterloo, Ontario: University of Waterloo Press; 1988.
2. Koo TK, Li MY. A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *J Chiropr Med.* 2016;15(2):155–163. doi:10.1016/j.jcm.2016.02.012

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Supplementary figures

Validation and population comparisons for maximum heel strike force.

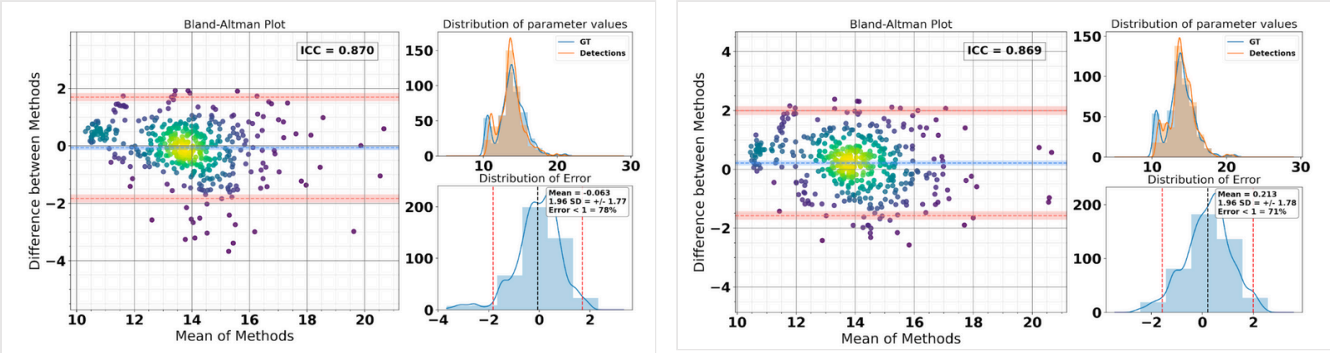


Figure S1. Validity of maximum heel strike force. Left: primary heel strike (ICC = 0.870). Right: secondary heel strike (ICC = 0.869). In each panel, the Bland–Altman plot (left) shows the difference between OneStep and the reference system against their mean; the dotted blue line is the mean difference and the red lines the 95% limits of agreement. The upper right inset shows the distributions of reference (GT) and OneStep values; the lower right inset shows the distribution of their difference.

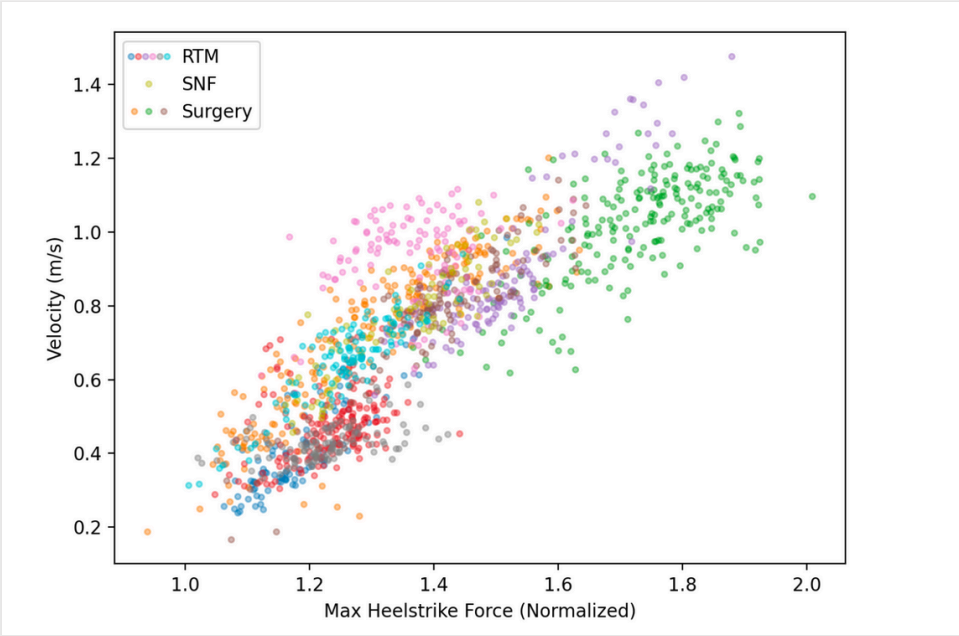


Figure S2. Maximum heel strike force versus walking velocity in 10 patients. Each color is one patient; marker groups denote care setting (RTM, SNF, surgery). Force and velocity are strongly related, yet individual patients occupy distinct bands at the same velocity.

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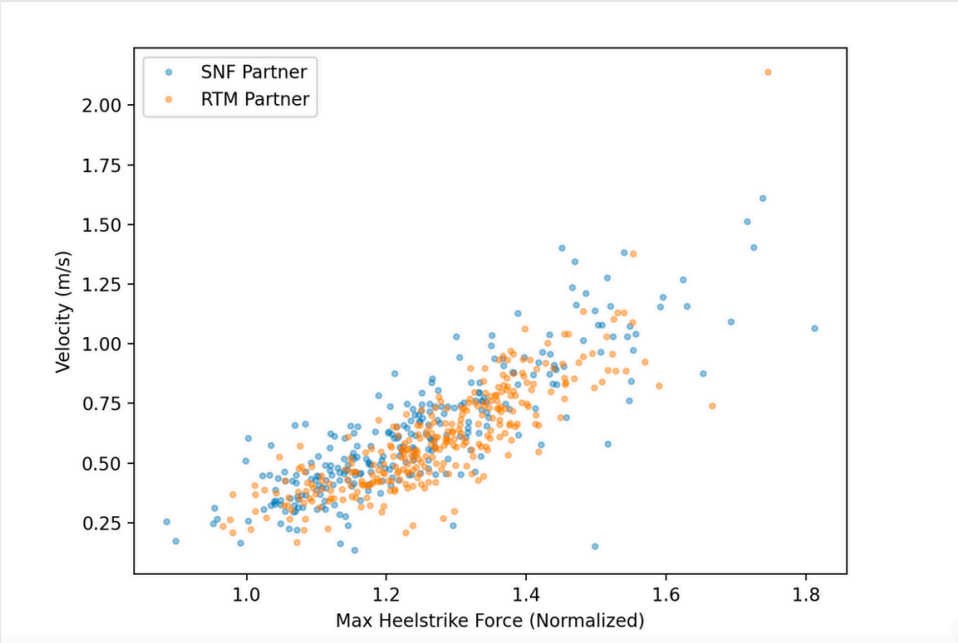


Figure S3. Maximum heel strike force versus walking velocity in a skilled nursing facility population and a remote therapeutic monitoring population.