# REQUIRED COEFFICIENT OF FRICTION ANALYSES IN RUNNING

**Andrea B. Vidal[1]; Lucas A. Monezi[1]; Karine J. Sarro[1]; Alysson F. Mazoni[1]; Heber T. Pinto[1]; Ricardo M. L. Barros[1]**

**Laboratory of Instrumentation of Biomechanics**
**Faculty of Physical Education, University of Campinas, Campinas, Brazil[1]**

The purpose of this study was to analyze the possible alterations in the required coefficient of friction (RCOF) in running under the following conditions: a) barefoot against shod; b) self-selected velocity and cadence versus imposed cadence and c) along three running phases (initial contact, mid-stance and propulsion). Two Kistler force plates were used to measure the horizontal and vertical components of ground reaction forces in order to calculate the RCOF. Statistical differences were found for cadence and phase factors. Barefoot-Shod conditions did not present statistical differences. An interaction between velocity and phase of cycle was found. At propulsion phase, an increased RCOF were revealed, especially with the interaction of an imposed cadence. In conclusion, the present study supports the relevance of RCOF as a variable affecting and being affected during running to be taken into consideration at many experimental conditions.

**KEY WORDS:** biomechanics, kinematic, force plate.

**INTRODUCTION:** The coefficient of friction (COF) at the imminence of the movement (static coefficient of friction) and that during the movement (dynamics coefficient of friction) are important predictors for the safety and efficiency of human movement (Blau, 2001). The COF is related to the dimensionless relationship between the frictional force and the normal force. Required coefficient of friction (RCOF) is the dynamic measure of the utilized COF and can be measured during motion. For safe locomotion it must be between static and dynamic coefficients of friction. The closer RCOF is from static coefficient, the larger the possibility of slip and fall. Therefore, RCOF is a critical parameter to predict risk of falling, according to (Chang, Chang, & Matz, 2011). Previous studies (Chang, Chang, & Matz, 2012; Rozin Kleiner, Galli, Araujo do Carmo, & Barros, 2015) investigated the RCOF in the normal and pathological gait determining parameters for the analysis of the friction curves. Cooper, Prebeau-Menezes, Butcher, & Bertram (2008) findings indicate that barefoot gait required greater coefficient of friction compared to shod subjects except at the shortest step lengths. Burnfield, Tsai, & Powers (2005) observed that during walking, at the fast speed, middle-aged subjects generated higher peak utilized COF values than elderly participants. To the best of our knowledge, there are no studies of RCOF in running. Furthermore, the better understanding of variables which influence RCOF while running could help to identify patterns related to fall accidents, injuries and performance. These variables are not understood in sports and daily activities as well as in normal and pathological gait. Thus, the aim of this study was to analyze the maximal values of RCOF ($RCOF_{max}$) under three experimental conditions: a) barefoot against shod; b) self-selected velocity and cadence versus imposed cadence; and c) compared at three phases of the stance phase.

**METHODS:** Twenty participants (12 males, 8 females, 29.4 ± 4.9 years, 70.42 ± 9.6 kg) were volunteers in this study. They were injury free three months prior to the test and trained over 15 km weekly in the last six months. The Research Ethics Committee has approved this study (protocol No. 1.552.726/2016) and the volunteers have given written informed consent to participate at this research. The participants were instructed to run in self-selected velocity and cadence with a standardized model of new running shoes (Nike Dual Fusion), and subsequently at an imposed cadence. The self-selected velocity and cadence was chosen by each participant as the proper training velocity. For the imposed cadence a metronome was used at the frequency of 180 bpm (to lead the participant perform 1.5 stride per second). The experiments in both cadences were also performed under barefoot and shod conditions. Force data were acquired at 500 Hz by two force plates (Kistler 9286BA), 0.60 m apart from each. The first plate was stepped always by the right foot. Data from both force plates were used to calculate the running speed and step length, however, to RCOF analyses, only the data from the first contact force plate were used. A threshold of 59 N in vertical force (Powers, Flynn, Brault, Burnfield, & Lim, 2002) was used to determine the beginning (0%) and ending (100%) percentage of running cycle. The stance phase in running was divided in three phases: 1- initial contact (0-25%), 2- mid-stance (25-75%) and 3- propulsion (75-100%) (Choi, Cha, Kim, Won, & Kim, 2015; do Carmo, Kleiner, & Barros, 2015). These phases were defined based on the RCOF pattern reported in gait cycle. The Ground Reaction Forces (GRF) were smoothed by a 4$^{th}$ order, low-pass Butterworth filter with a cut-off frequency of 10 Hz implemented in a MATLAB® code (Rozin Kleiner et al., 2015). COF was calculated as the ratio between the resulting horizontal forces and the normal force. The average RCOF curve (±SD) over subjects in function of running cycle was represented in order to characterize the variable in the three experimental conditions. The maximal values of RCOF ($RCOF_{max}$) in each of three phases of cycle were used for statistical analyses. Since data did not present normal distribution (Lilliefors Test), an analysis of variance of aligned rank transformed data was conducted (Wobbrock, Findlater, Gergle, & Higgins, 2011). So, a three-way ANOVA with repeated measures (mixed effects) were performed considering three factors: velocity (2 levels), shod (2 levels) and phases (3 levels). When significant differences were found, a *post hoc* pairwise comparison of levels within individual factors was performed by the Tukey method. Holm method for *p*-value adjustment was applied. For all tests, $p<0.05$ was adopted.

**RESULTS:** Figure 1 presents the average RCOF curve (±SD) over subjects in function of stance phase of running cycle. A consistent pattern can be recognized in the curves with higher values of RCOF at the beginning (0-25%) and ending of stance (75-100%). Higher variability can also be identified at the same two phases compared to mid-stance (25-75%). Tables 1 and 2 present $RCOF_{max}$ values in the three phases for all the experimental conditions and ANOVA results. Statistical differences were found for velocity (p=0.001) and phase (p<0.001) factors. Barefoot-Shod conditions did not present statistical differences (p=0.057). An interaction between velocity and phase of cycle was also found (p=0.007).

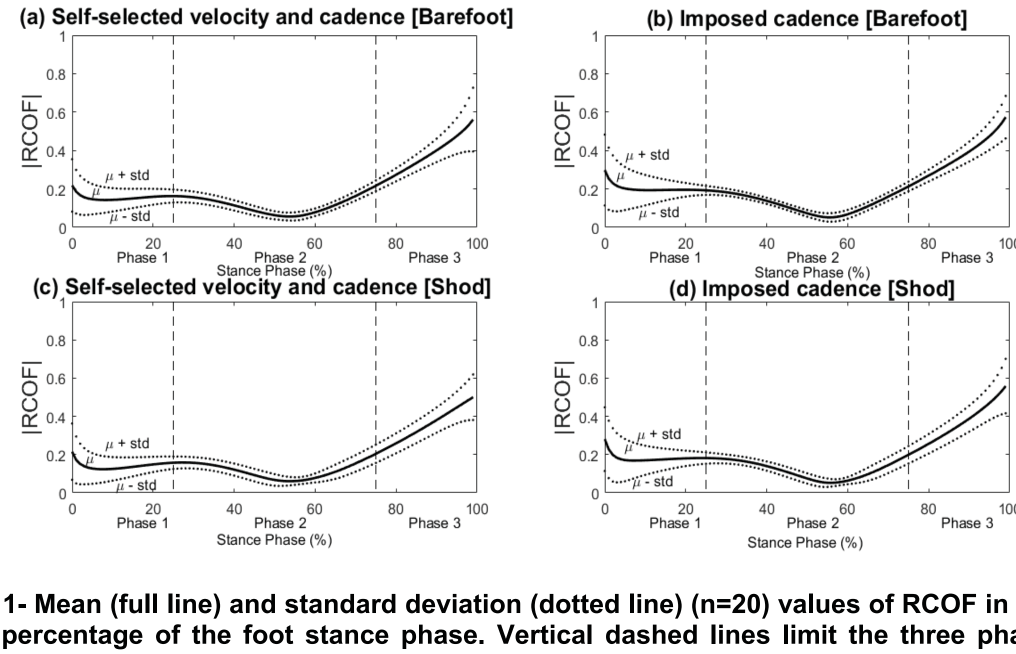


**Figure 1- Mean (full line) and standard deviation (dotted line) (n=20) values of RCOF in function of the percentage of the foot stance phase. Vertical dashed lines limit the three phases: (a) Self-selected velocity and cadence - barefoot; (b) Self-selected velocity and cadence - shod; (c) Imposed cadence - barefoot; (d) Imposed cadence - shod. The mean of self-selected velocity and cadence was 3.52 m/s and the mean of imposed cadence was 3.97 m/s.**

**Table 1**
**Maximal values of RCOF at the three phases for both conditions. Values presented as mean ± SD.**

| $RCOF_{max}$ | Phase 1: (0-25%) | | Phase 2: (25-75%) | | Phase 3: (75-100%) | |
|---|---|---|---|---|---|---|
| | Shod | Barefoot | Shod | Barefoot | Shod | Barefoot |
| Self-Selected Velocity and Cadence | 0.24±0.13 | 0.24±0.12 | 0.22±0.03 | 0.22±0.02 | 0.52±0.12 | 0.60±0.19 |
| Imposed Cadence | 0.30±0.15 | 0.32±0.16 | 0.22±0.02 | 0.22±0.02 | 0.59±0.16 | 0.61±0.13 |

**Table 2**
**Analysis of Variance of Aligned Rank Transformed Data. Deviance Table (Type III Wald F tests with Kenward-Roger Df, Model with Mixed Effects)**

| Effect | F | Df | Df. Res | Pr(>F) |
|---|---|---|---|---|
| Shod | 3.660 | 1 | 209 | 0.057 |
| Velocity | 11.091 | 1 | 209 | 0.001 * |
| Phase | 179.164 | 2 | 209 | <0.001 * |
| Shod:Velocity | 0.022 | 1 | 209 | 0.883 |
| Shod:Phase | 1.043 | 2 | 209 | 0.354 |
| Velocity:Phase | 5.005 | 2 | 209 | 0.007 * |
| Shod:Velocity:Phase | 0.675 | 2 | 209 | 0.510 |

* p<0.05

*Post hoc* test by Tukey Method showed that the maximal RCOF was smaller in the initial phase (0-25%) than the ending phase (75%-100) (p<0.001) and mid-stance phase presented smaller values compared to last part of cycle (p<0.001). No difference was found comparing the initial and mid-stance phase (p=0.160). Interaction analysis (*Post Hoc* Test by Holm Method) shows significant differences of cadence effect comparing phase 2 and 3 (p=0.037) and phase 2 and 1 (p=0.007). No significant interaction between cadence and phase was found comparing phase 1 and 3 (p=0.512).

**DISCUSSION:** The $RCOF_{max}$ in the three different phases of the stance phase revealed that the individuals present large variation in their initial contact and in propulsion. A hypothesis for this fact is a variation in the way the participants stepped the force plates. This is likely due the fact that the foot and shoe are not rigid bodies and interact in a flexible way with the force plates. $RCOF_{max}$ values in Table 1 show that coefficient of friction is greater when cadence is imposed. Also, the propulsion stage presents greater coefficient of friction when compared to initial contact and mid-stance. The RCOF is used to quantify the risk of falling and injuries that can occur due to individual or enviromental limitations in running. A phase with larger RCOF indicates a higher propension to slipping. In this phase a intervention can be made aimed at improving running. Pacifici et al. (2016) observed that slips are more likely in loading response and terminal stance phases. In general, the higher the RCOF, the more likely the ocurrence of slips, according to (Chang et al., 2011). It is possible to note that the values of RCOF in running are roughly of the same value when compared to running despite different surfaces and type of shoes as it is in (Anderson, Franck, & Madigan, 2014). Since imposed cadence has greater coefficient of friction, this condition represents a case with greater forces on the foot and energy expense.

**CONCLUSION:** Analysis of the RCOF is straightforward and gives important information on risk of falling while running. The phases of initial contact and propulsion had larger values of $RCOF_{max}$ which gives them greater importance in a training program. The results of the study support the need of taking into account the phase and cadence in order to understand the factors that influence the RCOF while running.

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