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"Effects of flooring on ground reaction forces and required coefficient of friction: elderly adult vs. middle-aged adult barefoot gait"

Ana Francisca Rozin Kleiner[a,b,d], Manuela Galli[c,d], Aline Araújo do Carmo[a,e], Ricardo M. L. Barros[a].

[a] Laboratory of Instrumentation for Biomechanics, College of Physical Education, University of Campinas, Campinas – Brazil.
Address: Avenida Érico Veríssimo, s/n, Barão Geraldo, Cidade Universitária "Zeferino Vaz", Caixa Postal 6134, CEP 13083-970, Campinas, São Paulo, Brasil.

[b] CAPES Foundation, Ministry of Education of Brazil, Brasília – DF, CEP: 70.040-020, Brazil.

[c] "Luigi Divieti" Posture and Movement Analysis Laboratory, Department of Electronics, Information and Bioengineering, Politecnico di Milano, Milano – Italy.
Address: Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria - Piazza leonardo da Vinci 32 - 20133 Milano, Italia.

[d] "Motion analysis Lab", IRCCS San Raffaele Pisana, Via della Pisana, 235, Rome – Italy.

[e] University of Brasilia, Brasília – Brazil. QNN14, Área Especial, Ceilândia Sul, Distrito Federal, CEP: 72.220-710.

Ana Francisca Rozin Kleiner (Corresponding Author)
Phone numbers: (+39)3396234673 / (+5519)3521-6626.
Address: Avenida Érico Veríssimo, s/n, Barão Geraldo, Cidade Universitária "Zeferino Vaz", Caixa Postal 6134, CEP 13083-970, Campinas, São Paulo, Brasil.
E-mail address: anafrkleiner@gmail.com

Manuela Galli
E-mail address: manuela.galli@biomed.polimi.it

Aline Araújo do Carmo
E-mail address: alinecarmo@unb.br

Ricardo Machado Leite de Barros
E-mail address: ricardo@fef.unicamp.br

ABSTRACT

The aim of this study was to investigate the effect of flooring on barefoot gait according to age and gender. Two groups of healthy subjects were analyzed: the elderly adult group (EA; 10 healthy subjects) and the middle-aged group (MA; 10 healthy subjects). Each participant was asked to walk at his or her preferred speed over two force plates on the following surfaces: 1) homogeneous vinyl (HOV), 2) carpet, 3) heterogeneous vinyl (HTV) and 4) mixed (in which the first half of the pathway was covered by HOV and the second by HTV). Two force plates (Kistler 9286BA) embedded in the data collection room floor measured the ground reaction forces and friction. The required coefficient of friction (RCOF) was analyzed. For the statistical analysis, a linear mixed-effects model for repeated measures was performed. During barefoot gait, there were differences in the RCOF among the flooring types during the heel contact and toe-off phases. Due to better plantar proprioception during barefoot gait, the EA and MA subjects were able to distinguish differences among the flooring types. Moreover, when the EA were compared with the MA subjects, differences could be observed in the RCOF during the toe-off phase, and gender differences in the RCOF could also be observed during the heel contact phase in barefoot gait.

Keywords: gait, elderly, risk of falls, barefoot.

Barefoot gait on carpet revealed higher required coefficient of friction than vinyl flooring.

The results of the present study showed different behavior between EA and MA subjects with respect to RCOF.

Females presented higher RCOF values during heel contact.

Friction on barefoot gait is affected by flooring types, gender and age.

Carpet was the safer flooring in terms of required coefficient of friction.

1. Introduction

The causes of falling are multifactorial and can be due to individual limitations, environmental conditions or the interaction of both effects. Among the individual limitations that can increase the probability of falls are balance and gait disorders, side effects of certain medications and the effects of aging (Salzman, 2010; Silva-Smith et al., 2013). In particular, many falls experienced by older adults occur when a change in body position is required, such as walking on different flooring.

Previous research has investigated the effects of age on the ability to walk on different flooring, e.g., carpet versus vinyl (Willmott, 1986; Dickinson et al., 2001). However, contradictory results were found depending on the gait velocity on these flooring types (Willmott, 1986; Dickinson et al., 2001). Changes in gait speed and step length during ambulation over two different surfaces such as carpet and vinyl flooring may influence the outcome of slips and falls, especially for the elderly. Understanding how older adults adapt to walking on different flooring types may provide useful information for the design of interventions to reduce falls in older people.

The surface roughness of the shoe and floor surfaces affects slipperiness significantly (Kim et al, 2013; Kim and Nagata, 2008; Chang et al., 2012; Lockhart et al., 2003), and dangerous slips are most likely to occur when the required coefficient of friction (RCOF) at the shoe-floor interface exceeds the available coefficient of friction of the floor (Kim et al, 2013; Kim and Nagata, 2008). The RCOF is one of the most critical gait parameters in predicting the risk of slipping (Chang et al, 2012). It is defined as the minimum coefficient of friction necessary at the shoe-floor interface to support walking, and its value relative to the environmentally coefficient of friction is used to assess the probability of slipping (Chang et al, 2012; Redfern et al., 2001;

Hanson et al., 1999). Consequently, slip severity increases as the difference between the RCOF and the available coefficient of friction of the floor surface increases (Kim et al, 2013; Kim and Nagata, 2008ab, Chang et al., 2012; Lockhart et al., 2003; Hanson, 1999).

At the interface between the foot and the ground, footwear is likely to influence balance control and the risk of experiencing slips and trips while walking. The shoe type and sole material affect the available friction between the foot and the support surface. Because many falls occur when older adults walk barefoot inside their home or in a familiar environment (Menz et al, 2006), understanding their behavior while walking barefoot on different flooring should provide new insights about the risk of falls in the elderly population.

In general, elderly adults walk slower than young adults, with a higher heel contact velocity and a shorter step length (Lockhart, 1997; Lockhart et al, 2003; Burnfield and Powers, 2003; Kim and Lockhart, 2006; Menz et al, 2006; Seo and Kim 2013). It has been suggested that these age-related gait adaptations influence the likelihood of slip-induced falls (Lockhart et al., 2003). Another factor that should be taken into account is gender differences. According to Lach (2005), gender is the most important covariant associated with the fear of falling. Women with balance and gait difficulty resulting in unsteadiness, multiple falls, and low self-rated health are at greatest risk (Lach, 2005).

Although fall risk factors among the elderly have been well studied (Lockhart, 1997; Lockhart et al, 2003; Burnfield and Powers, 2003; Kim and Lockhart, 2006; Menz et al, 2006; Seo and Kim 2013), it could be interesting to understand the strategies adopted by middle-aged and elderly adults when walking over different flooring. We are interested in comparing older adults (60-70 years old) (O'Loughlin et al, 1994), whose risk of falling is relatively high, with a group of adults close in age (40-50 years old) with a lower risk of falling. Previous studies have only compared RCOF strategies in the elderly with control groups of young adults (20-30 years old) (Lockhart, 1997; Lockhart et al, 2003; Burnfield and Powers, 2003; Kim and Lockhart, 2006; Menz et al, 2006; Seo and Kim 2013).

Therefore, the aim of this study was to investigate the effect of flooring on the RCOF during barefoot gait according to age (middle-aged versus elderly adults) and gender. Our goal was to test the following hypotheses: (a) differences in the RCOF variables can be found during barefoot gait on different flooring; (b) differences can be observed in the RCOF between elderly adults and middle-aged adults; and (c) gender differences in the RCOF can be observed during barefoot gait.

2. Material and Methods

Participants

The Research Ethics Committee of the University of Campinas approved this study (UNICAMP protocol No. 319/2011), and the volunteers gave written informed consent to participate. Twenty healthy subjects volunteered in this study, and they were divided into two age groups: elderly adults (EA, n=10) and middle-aged adults (MA, n=10). Table 1 shows the anthropometric data for each group. The subjects recruited for this study were healthy (without known musculoskeletal, neurologic, cardiac, or pulmonary diagnoses), community dwelling, and ambulatory without an assistive device.

Insert Table 1 near here.

Flooring Classification

Three flooring types under four experimental conditions were used to evaluate the study volunteers:

- ***Homogeneous vinyl (HOV):*** Homogeneous single-layer vinyl flooring (Pavifloor Prisma tile, 2 mm thickness, 2X8 m, ref. 909, charcoal, Tarkett Fademac);
- ***Heterogeneous vinyl (HTV***): Compact flexible vinyl floor covering (Chinese Teak natural, 2.50 mm thickness, 2X8 m, Imagine Wood, Tarkett Fademac);
- ***Carpet:*** Needle-punch carpet (plain quality needle-punch carpet, 100% pet fiber, 2 mm thickness, 2X8 m, Flortex Eco Inylbra);
- ***Mixed:*** To simulate a person walking from one room to another room with different flooring, a mixed condition was included. As illustrated in Figure 2d, the first 4 m of the pathway was covered by HTV, and the second 4 m of the pathway was covered by HOV.

To characterize the flooring used in this study, the static coefficient of friction (μ_e) was calculated using a pulley test. Figure 1a illustrates the test and the resulting $\mu_{e.}$. The chosen flooring was positioned on a force platform (Kistler 9286BA), and over this flooring a halter (H1) was positioned weighing 18.42 kg. Halter H1 was pulled by another halter (H2) weighing 17.32 kg. H1 was connected to H2 by a steel cable that slid on a system of three rollers, one fixed on the floor (R1) and two on the laboratory roof (R2 and R3). From the plot of the coefficient of friction of the force plate as a function of time, μ_e was determined as the maximum friction prior to the start of movement. The μ_e values for all the flooring chosen for this study were approximately

0.5, which is within the standards of safety according to Templer (1992) and Miller (1983) (see Figures 1b, 1c, 1d and 1e).

Insert Figure 1 near here.

Experimental Procedures

The participant was asked to walk barefoot, at his or her selected speed, along a pathway of the experimental flooring material, beneath which two force platforms (Kistler 9286BA) were embedded in the data collection room floor, as shown in Figure 1. Possible effects of the participant's chosen speed on the results were tested, and no significant differences were found related to the flooring condition (p=0.710), age group (p=0.944) or gender (p=0.417). The participants were aware of the force plate locations. Three trials were performed for each experimental condition. Because of the difficulties associated with changing flooring conditions, all subjects accomplished the tasks in the same order: HOV, carpet, HTV and mixed.

The ground reaction force data were normalized by the subject's body weight (%BW) and expressed as a function of the percentage of the support phase. Data acquisition was performed using BioWare software (Version 4.0.x). Kinetic raw data were filtered using a 2^{nd} order low-pass digital Butterworth filter with a cut-off frequency of 10 Hz. An algorithm developed in Matlab was used to filter the raw data and to calculate the dependent variables.

The independent variables were the type of surface (HOV, HTV, carpet or mixed), age group (AG or EG) and gender (female or male). The discrete variables used in the study were as follows.

To calculate the RCOF (required coefficient of friction), the instantaneous COF was first calculated as the ratio of the shear to the normal ground reaction force during stance (Chang et al, 2012; Redfern et al., 2001—see equation 1 and Figure 2). According to Chang et al. (2012), the RCOF is typically considered to be the local maximum of the instantaneous COF curve occurring at ~20% of the duration of the stance phase of gait, during weight acceptance, identified as ***RCOF1*** in Figure 2. Also according to Chang et al. (2012), another local maximum occurs at ~90% of the duration of the stance phase of gait, during push-off, identified as ***RCOF2*** in Figure 2. This peak is thought to be associated with a lower risk for a slip-induced fall (Chang et al, 2012; Redfern et al., 2001).

$$\text{COF} = \frac{\sqrt{(FY)^2+(FX)^2}}{FZ} \quad (1)$$

Insert Figure 2 near here.

A two-sample t-test was performed to compare the anthropometric variables (height and weight) between age groups. A linear mixed-effects model (West et al., 2007) for repeated measures was performed to analyze the possible effects of flooring, age and gender on the dependent friction variables. The repeated covariance type chosen for the mixed linear model was scaled identity. Three trials for each flooring condition were considered in the statistical procedures. The model applied used three main factors. The first analysis factor was the flooring, which was treated as a repeated measures factor with four sublevels (HOV, carpet, HTV and mixed). The second factor analyzed was age, with two sublevels (EA and MA). The third factor was gender (male and female). The first effect was considered as a within-subjects factor, and the second and third effects were considered as between-subjects factors. The Bonferroni test of pairwise comparisons was computed for every level of combination of factors and interactions. SPSS software (SPSS for Windows, version 19.0) was used for the statistical analysis, with a level of significance of $\alpha<0.05$ for all tests.

The partial eta squared ($\eta^2_{partial}$) value was calculated as in Equation 2 to verify the practical relevance of the main effects and interactions. As proposed by Richardson (2011), in this study, partial η^2 values >0.01 were categorized as low, >0.06 as medium, and >0.14 as high.

$$\boldsymbol{\eta^2_{partial}} = \left(\frac{\text{Full model residual variance}}{\text{Full model residual variance+Reduced model residual variance}}\right) \qquad (2)$$

3. Results

The two-sample t-test revealed no significant differences between the EA and MA groups for body mass ($F_{1,19}$=0.206; p=0.655) and height ($F_{1,19}$=0.007; p=0.936).

The mixed model analysis revealed significant differences for the three main factors (flooring, age and gender), with no interaction between them. When the flooring types were compared during the loading response phase, the participants demonstrated a greater RCOF1 on carpet than on the HOV or HTV flooring ($F_{3,480}$=3.273; p=0.021; $\eta^2_{partial}$=0.68; Figure 3a). The $\eta^2_{partial}$ value shows that the relevance of this effect was high.

In the push-off phase, the RCOF2 was statistically greater when the subjects walked on carpet than when they walked on the HOV flooring, with a medium level of practical relevance for this main factor ($F_{3,480}$=4.182; p=0.006; $\eta^2_{partial}$=0.11; Figure 3b).

Insert Figure 3 near here.

The EA group had statistically smaller RCOF2 values than the MA group, with a high practical relevance for the factor ($F_{1,480}$=42.948; p=0.0001; $\eta^2_{partial}$=0.61; Figure 4a). Moreover, when gender effects were compared, the male subjects had a lower RCOF1 than the female subjects, with a medium level of practical relevance ($F_{1,480}$=7.979; p=0.005; $\eta^2_{partial}$=0.04; Figure 4b).

Insert Figure 4 near here.

4. Discussion

This research project was undertaken to provide a better understanding of how flooring, age and gender influence foot-floor friction in the gait of healthy middle-aged and elderly male and female subjects. Barefoot gait was selected for analysis because according to Menz et al. (2006), a higher risk of falling indoors is associated with going barefoot. The required coefficient of friction at the loading response and push-off phases of gait were used as experimental variables because it is well known in the literature that these variables are related to the risk of a fall and also make it possible to mechanically characterize the foot-floor interaction.

The main result obtained in the present study was that the three main factors tested in the statistical model (flooring, age and gender) were significant and had practical relevance ranging from medium to high. No interaction was found among flooring, age and gender; therefore, no conclusion was possible regarding distinctive behaviors of the EA or MA groups, or of the male or female participants, with each flooring type.

The RCOF was higher during barefoot gait on carpet than on vinyl flooring (HTV and HOV) in the deceleration phase of gait (i.e., the loading response) as well as in the push-off phase (i.e., the terminal stance), confirming the first hypothesis of the present study and suggesting that carpet is the safest flooring of the three types analyzed in the present study.

It is well known that surface roughness plays an important role in floor slipperiness when subjects wear walking shoes (Kim et al, 2013; Kim and Nagata, 2008; Chang et al., 2012; Lockhart et al., 2003). Our results confirm this finding in barefoot walking.

The effect of the flooring condition on the friction variables was not surprising; however, it demonstrates that this aspect should be considered during gait analyses and gait investigations. Because friction is a relevant factor in gait patterns, the proper description and control of this variable are important for experimental design in gait analysis. However, because these variables are related to age and gender, they could be used alone or in correlation in further studies.

The study found different RCOF behavior in the EA and MA subjects. This could be due to plantar sensitivity. Plantar sensitivity is an important source of information for balance control because it codifies the changes in pressure under the feet, especially during gait. This information reaches the brain, which senses the body position and, if necessary, generates postural reflexes to maintain an upright position and dynamic balance during gait (Kavounoudias et al., 1998; Wang and Lin 2008).

Compared to the barefoot condition, walking shoes could potentially interfere with the detection of plantar surface stimulation. Such interference might be inconsequential for individuals with intact plantar sensitivity. However, EA often have reduced plantar sensitivity (Perry, 2006).

A further reduction in plantar sensory feedback while walking barefoot might lead to insufficient afferent input for locomotion control in EA and MA, and consequently, a cautious gait might need to be adopted. Further studies are needed to determine the relationship between barefoot gait plantar sensitivity and the effect of more challenging flooring on gait. A false subjective perception of slipperiness might lead to an inappropriate gait pattern, which might result in a higher probability of a slip-induced fall in the elderly population.

The results of the present study are in agreement with previous studies that have shown that the peak RCOF varies with age (Lockhart, 1997) and gender (Burnfield and Powers 2003).

When the age groups were compared, the EA group had a lower RCOF during the toe-off phase. This adaptation is thought to result in more stable or safer gait patterns in the elderly. Future studies exploring this developmental effect could attempt to determine the exact time at which the risk of falls becomes pronounced in this population and could also investigate the possibility of effective interventions to reduce falls in the elderly population.

There were also gender differences in the RCOF. Female participants had higher RCOF values during heel contact. This was also observed by Li et al. (2001) and Chao et al. (1983), who found that women exhibited greater vertical GRF than men. Burnfield and Powers (2003) found that the peak RCOF varied with gender; females generated higher peak RCOF values than males at a slow walking speed, whereas males generated higher peak RCOF values than females at a fast walking speed. The structural differences in the female hip and knee may result in differences in their movement patterns (Mizuno et al., 2001; Ferber et al., 2003). This suggests that some intrinsic characteristics, such as skeletal alignment, muscle strength and anthropometric parameters, may contribute to gender and age differences in gait performance.

In conclusion, friction during barefoot gait was found to be affected by flooring type, gender and age. Carpet was the safest flooring in terms of the required coefficient of friction. When elderly adults were compared to middle-aged adults, they demonstrated a reduced required coefficient of friction during the toe-off phase, and gender differences were observed in the RCOF during the heel contact phase in barefoot gait.

Much of the research on falls has focused on how the aging process affects gait. The problem with this clinical focus is that little thought has been given to the environment, such as flooring differences in the patient's home. The fact that EA are particularly challenged under these circumstances could be exploited in designing rehabilitation exercises to improve functional mobility and reduce falls with advanced age; in particular, the role of patients' plantar sensitivity during barefoot gait could be explored. In fact, a reduced incidence of falling in EA has been demonstrated following an exercise intervention using an obstacle course designed with different flooring conditions and obstacles to foot placement.

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FIGURE LIST

Figure 1. Illustration of the pulley test (a) and the flooring conditions with the pulley tests results: Homogeneous Vinyl (HOV - b); Carpet (c); Heterogeneous Vinyl (HTV – d); Mixed (HOV and HTV – e).

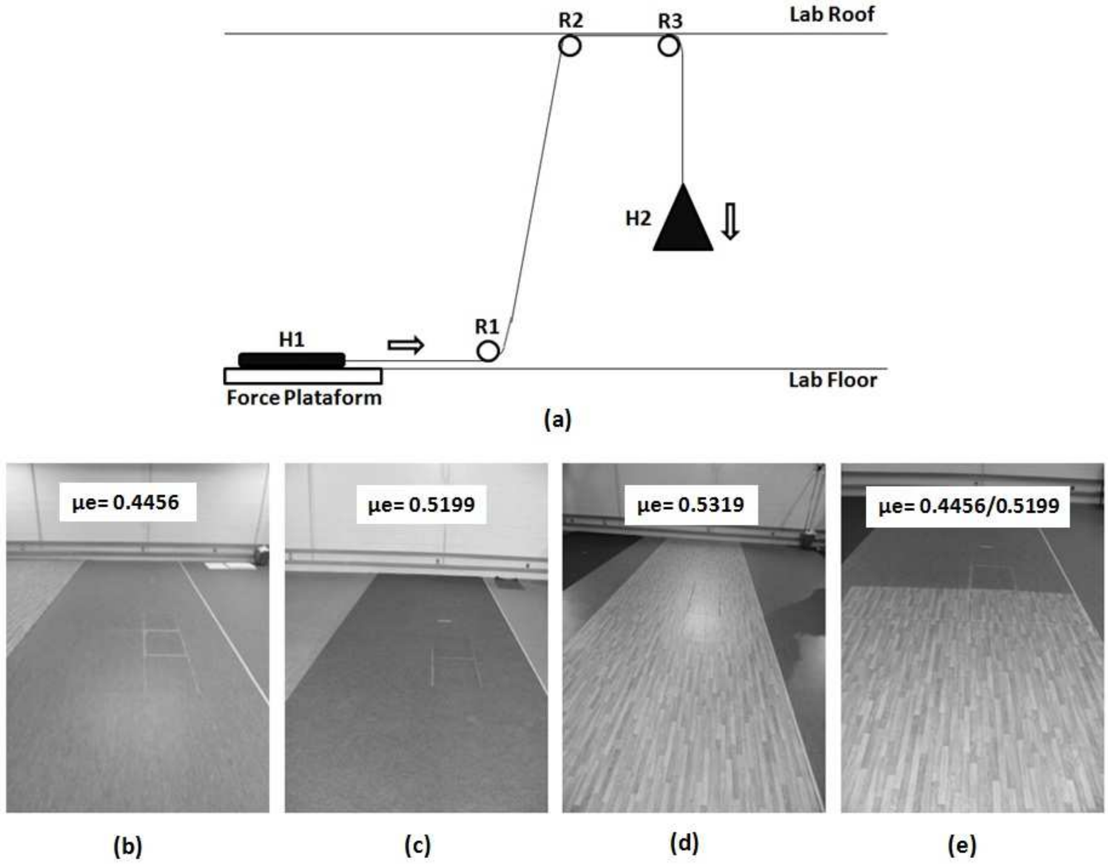
Figure 2. Illustration of the RCOF curve represented by the average curve over all healthy females participants in the HOV condition.

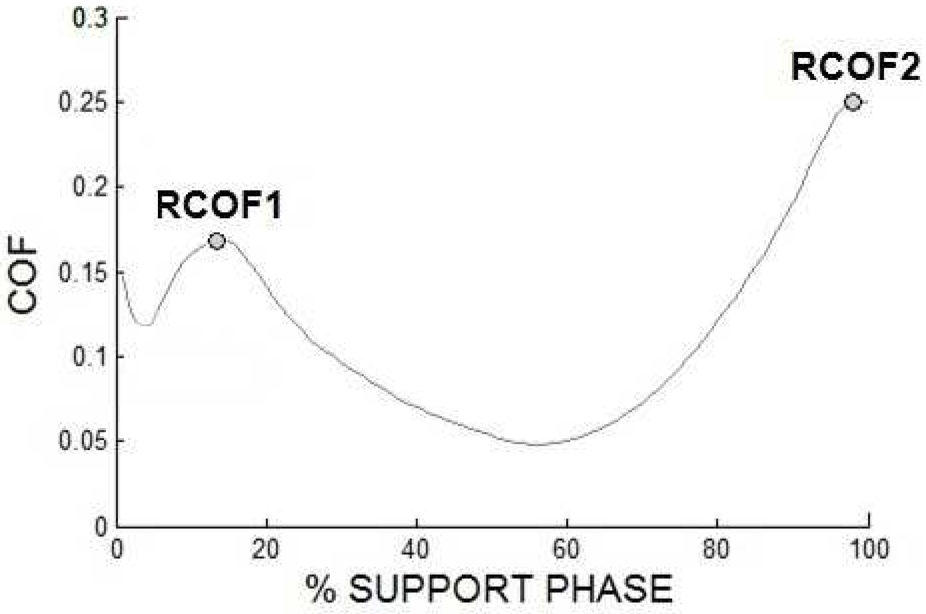
Figure 3. Required coefficient of friction at loading response (RCOF1) and push-off (RCOF2) phases of gait. Values expressed in terms of means and standard deviation. Legend: * = $p<0.05$.

Figure 4. Means and Standard deviations and statistical results for Age (a) and gender (b) effects. Legend: * = $p=0.001$.

TABLE LIST

Table 1. Anthropometric data. Legend: EA = Elderly Adult group; MA = Middle-aged Adult group; N = sample size.


Lab Roof
R2
R3
H2
H1
R1
Lab Floor
Force Plataform
(a)
μe= 0.4456
μe= 0.5199
μe= 0.5319
μe= 0.4456/0.5199
(b)
(c)
(d)
(e)



RCOF2
RCOF1
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80
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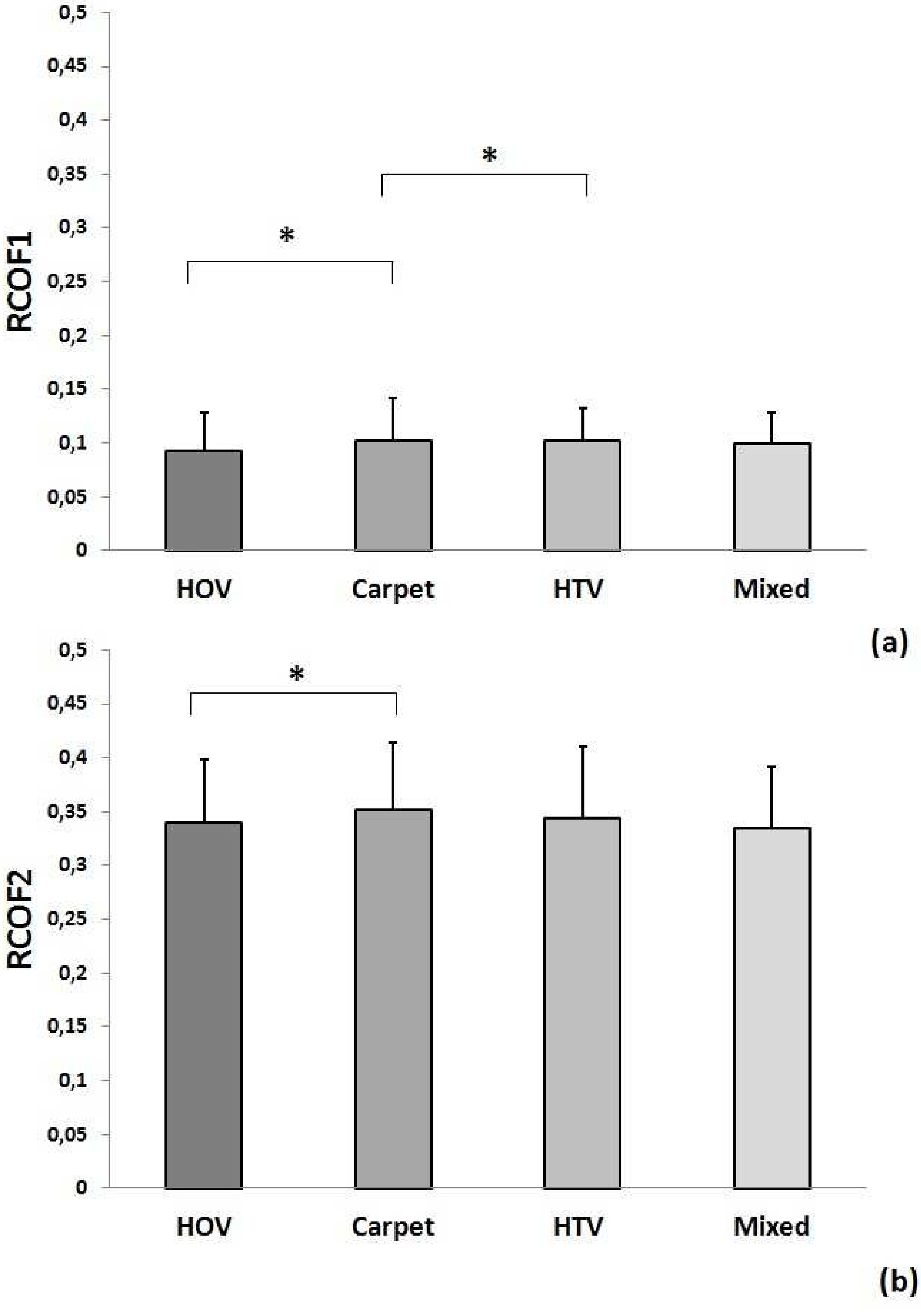
% SUPPORT PHASE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HOV
Carpet
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Mixed
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RCOF2
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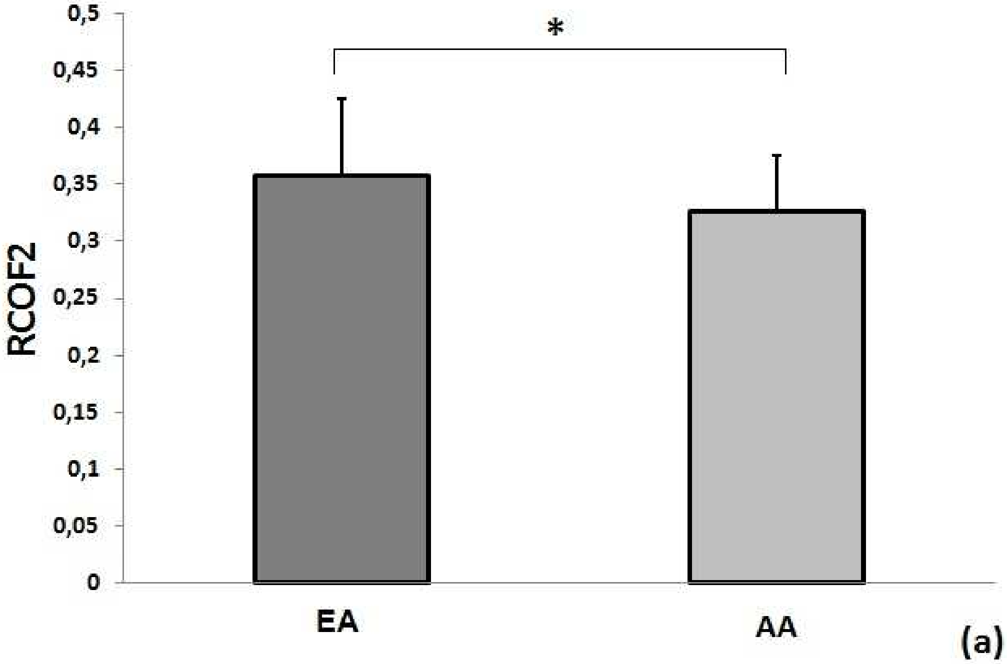
HOV
Carpet
HTV
Mixed
(b)


RCOF2
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EA
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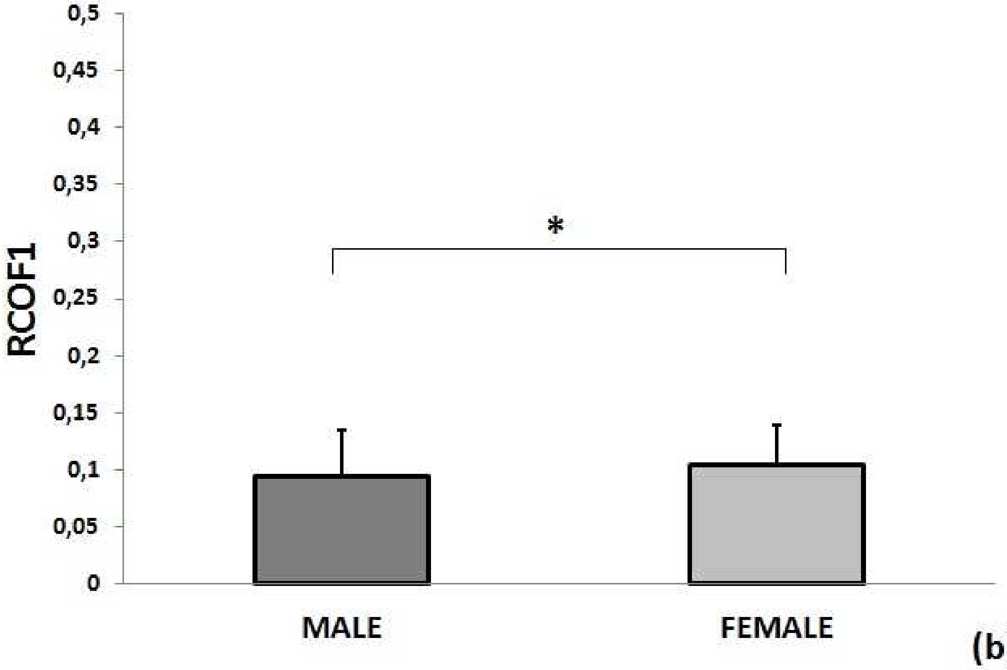
(a)


RCOF1
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0
*
MALE
FEMALE
(b)

Table 1. Anthropometric data.

Group	N	Age (years)	Body Mass (kg)	Height (cm)
EA males	5	67.4±5.02	74.52±14.21	164.04±11.44
EA females	5	67.8±6.05	69.80±16.34	162.5±6.64
MA males	5	48.2±6.22	78.75±8.23	166.58±9.28
MA females	5	47.6±3.32	70.76±11.98	166.24±8.21
EA	10	67.6±5.25	72.17±14.66	166.41±8.26
MA	10	47.90±5.47	74.76±10.57	163.27±8.85
Males	10	57.7±11.92	70.28±13.52	164.37±7.3
Females	10	57.8±11.43	76.64±11.17	162.31±9.91

Legend: EA = Elderly Adult group; MA = Middle-aged Adult group; N = sample size.