

Article

Hallux Strength Matters: Its Relationship with Physical Performance and Predictive Role in Fall Risk

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Abstract

Background: Reduction in intrinsic foot muscle strength may impair physical performance and increase the risk of falls. **Aim:** The aim of this study is to analyze the relationship between hallux flexion strength, assessed through the PGT, for physical performance and fall risk in Chilean older adults. **Methods:** A cross-sectional, descriptive–correlational study was conducted with 188 community-dwelling older adults (89.3% women). Participants’ sociodemographic and anthropometric information was also collected. Hallux plantar flexion strength was assessed using the Paper Grip Test (PGT). Physical performance was evaluated with the Short Physical Performance Battery (SPPB), and fall risk was assessed using the Timed Up and Go (TUG) and Single-Leg Stance Test (SLS). Pearson’s correlation coefficients were calculated for the overall sample, as well as separately for sex. **Results:** Significant positive correlations were observed between PGT and the total SPPB score for both the right foot ($r = 0.178$; $p = 0.008$) and the left foot ($r = 0.175$; $p = 0.009$). Additionally, moderate correlations were found between PGT and SLS time (right $r = 0.316$; $p < 0.001$; left $r = 0.397$; $p < 0.001$), and an inverse correlation was observed between PGT and TUG execution time (right $r = -0.372$; $p < 0.001$; left $r = -0.393$; $p < 0.001$). Regression models showed that TUG and SLS significantly predicted PGT performance, explaining 17% ($R^2 = 0.17$) and 20% ($R^2 = 0.20$) of the variance for the right and left foot, respectively. **Conclusions:** Hallux plantar flexion strength is significantly associated with physical

performance and fall risk. The simplicity, low cost, and clinical utility of the PGT support its use as a screening tool for early detection of functional decline.

Keywords: toe flexor; fall risk; paper grip test; older adults; lower limb strength

1. Introduction

Aging is a complex and multifactorial process characterized by the progressive accumulation of molecular and cellular damage, which disrupts homeostasis and impairs the functionality of various physiological systems [1,2]. This deterioration has a particularly significant impact on the musculoskeletal system, leading to a sustained decline in muscle mass, strength, and physical performance, which directly affects functional capacity and autonomy in older adults [2]. One of the most clinically relevant manifestations of this decline is sarcopenia, defined by the European Working Group on Sarcopenia in Older People (EWGSOP2) as a progressive and generalized muscle disease, primarily diagnosed by the loss of muscle strength, and accompanied by a reduction in muscle mass and/or physical performance [3]. Sarcopenia is a key determinant in the loss of functional capacity, with well-documented consequences, such as increased risk of falls, disability, institutionalization, and mortality [4–6]. Globally, its prevalence is estimated to range between 1% and 10% [7]. In Chile, however, a recent study reported a higher prevalence of 18.8% among community-dwelling older adults [8], underscoring its emergence as a pressing public health concern in rapidly aging societies.

Among the key components of sarcopenia, physical performance is one of the most affected functional domains [9]. This is understood as the ability to efficiently and safely perform activities of daily living, as well as occupational or recreational tasks [10,11]. Its decline is clinically manifested by reduced gait speed, difficulties in maintaining balance and performing postural transfers, and an increased risk of falls [12]. Falls, in turn, are considered one of the major geriatric syndromes, with devastating consequences in terms of morbidity and mortality, loss of functional independence, and increased burden on healthcare systems [13,14]. According to estimates from the World Health Organization (WHO), approximately 684,000 people die each year as a result of falls, making them the second leading cause of death from unintentional injuries. Additionally, it is reported that between 28% and 35% of adults aged 65 and older experience at least one fall annually, a percentage that rises to 42% among those over 70 years old [15]. In this context, the early identification of musculoskeletal factors associated with fall risk becomes particularly relevant within geriatric assessment [13]. Timely detection of these alterations not only allows for the anticipation of adverse events but also facilitates the implementation of preventive interventions aimed at preserving autonomy and improving the quality of life in older adults.

Recent evidence has drawn attention to the role of lower limb muscle weakness—particularly the intrinsic foot muscles such as the hallux flexors—as a potentially underrecognized contributor to fall risk and reduced physical performance in older adults [16,17]. Although traditionally overlooked in geriatric assessment, the functional capacity of the foot's intrinsic musculature is gaining scientific interest due to its critical role in forefoot stabilization, dynamic control of the center of pressure, and efficient execution of the propulsive phase of gait [18,19]. For its clinical assessment, the Paper Grip Test (PGT) has been proposed as a valid, reliable, and low-cost screening tool that allows for the direct quantification of hallux flexor strength through a standardized, simple protocol applicable in both clinical and community settings [20,21]. It has been reported that the values obtained through this test not

only reflect the strength of the intrinsic foot muscles but also show significant correlations with overall lower limb strength and general functional capacity [20]. Additionally, it has demonstrated moderate-to-high correlations with total ankle–foot strength, indicating its ability to discriminate older adults at high risk of falling, even outperforming conventional screening tools [22].

Nevertheless, despite its potential as a screening test, the evidence supporting the use of the PGT remains limited, especially in Latin American contexts. Most existing studies have been conducted in European and Asian populations, which reduces the generalizability of their findings to other epidemiological and sociocultural realities [20,22,23]. This paucity of region-specific research also limits the integration of the PGT into functional assessment protocols within community settings, the primary healthcare system, and preventive strategies targeting musculoskeletal decline in older adults. The incorporation of functional assessment tools in regional contexts is not only a methodological need but a clinical imperative, given the epidemiological disparities and structural differences that exist across health systems. In this context, we hypothesized that examining hallux plantar flexion strength in Chilean older adults would provide evidence on its association with physical performance and fall risk, thereby addressing a critical gap in the current literature.

Given the rapid aging of the Chilean population and the functional consequences associated with sarcopenia, it is a priority to identify direct indicators of muscle strength that are accessible and clinically applicable, enabling early assessment of functional decline and detection of fall risk. Therefore, the objective of the present study was to analyze the relationship between hallux flexion strength, assessed through the PGT, and both physical performance and fall risk in Chilean older adults.

2. Materials and Methods

2.1. Design and Participants

A quantitative, descriptive–correlational study was conducted using a cross-sectional observational design [24], including 188 older adults of both sexes, recruited through non-probability convenience sampling. Inclusion criteria were individuals aged 60 years or older, of either sex, with preserved cognitive function as assessed by the Abbreviated Mini-Mental Test (score ≥ 14 points, a cutoff validated in the Chilean population to discriminate between preserved and impaired cognition) [25]; and ability to independently perform activities of daily living according to the Functional Assessment for Older Adults [26]. Participants were excluded if they presented any condition that interfered with the administration of physical tests, such as severe physical disability, use of assistive devices for ambulation, acute musculoskeletal injuries or limiting pain, limb amputations, a clinical diagnosis of hallux valgus, or a history of surgery on the hallux [21]. Additionally, individuals with active dermatological conditions affecting the feet, such as ulcers, edema, osteomyelitis, gangrene, burns, or skin diseases, that could compromise the proper execution of the test were also excluded (Figure 1).

All participants provided written informed consent, which stated that the evaluation posed no health risks and that they were free to withdraw from the study at any time without consequences, in accordance with the principles of the Declaration of Helsinki.

The required sample size was calculated a priori using the software G*Power 3.1.9.7 (Universität Düsseldorf, Düsseldorf, Germany), applying an F-test for linear multiple regression (fixed model, R^2 deviation from zero). The calculation was based on the following parameters: medium effect size ($f^2 = 0.15$), significance level ($\alpha = 0.05$), statistical power ($1 - \beta = 0.80$), and seven predictors in the regression model. The analysis indicated that a minimum of 103 participants were required to detect statistically significant associations.

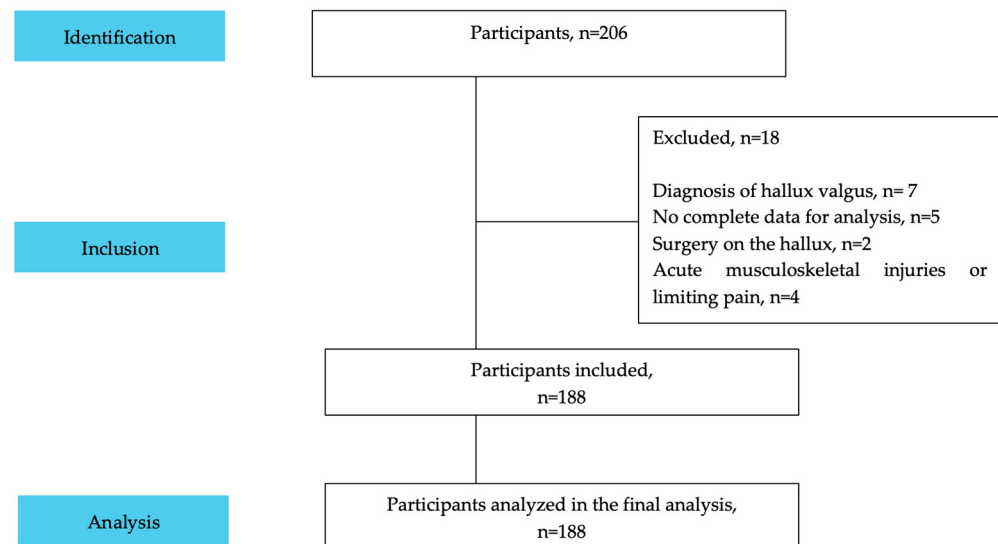


Figure 1. STROBE flowchart of participants.

2.2. Procedures

All physical assessments were conducted by two trained evaluators, both of whom underwent a standardized training process to ensure consistency in the administration of all procedures. The training included detailed familiarization with the test protocols, supervised practice sessions, and inter-rater reliability checks to minimize measurement bias.

Evaluations were performed in the Physical Activity Sciences Laboratory of the Universidad Autónoma de Chile, under optimal testing conditions. The laboratory provided a controlled indoor environment with ample space, stable flooring, adequate lighting, and temperature regulation, allowing for standardized and uninterrupted application of the physical performance tests.

Body weight was measured using a calibrated digital scale (model 769, SECA, Hamburg, Germany), with participants standing barefoot, in the anatomical position, with the head aligned in the Frankfurt plane, arms relaxed at the sides, and without external support. Height was assessed using a portable stadiometer (model 213, SECA), with the participant standing upright, heels together, back straight, and gaze directed forward. Body mass index (BMI) was then calculated using the formula $\text{weight (kg)}/\text{height}^2 \text{ (m}^2\text{)}$ and interpreted according to the WHO classification criteria. Waist circumference (WC) was measured using a non-extensible measuring tape (model 201, SECA, Hamburg, Germany), positioned at the midpoint between the lowest rib and the iliac crest, with the participant in a standing position in bipedestation and during normal expiration, in accordance with standardized International Society for the Advancement of Kinanthropometry procedures [27].

2.2.1. Hallux Plantar Flexion Strength

Hallux plantar flexion strength was assessed using the PGT, employing a digital traction dynamometer (model PCE-FG 20SD, PCE Instruments, Meschede, Germany). The participant was seated on a chair with the hip, knee, and ankle joints at 90°, and the arms relaxed at the sides of the body [23]. The test was performed without shoes or socks, with the foot fully supported on the floor. The examiner positioned a card attached to the dynamometer just beneath the hallux, distal to the metatarsophalangeal joint, following the protocol described by Chatzistergos et al. [23]. The participant was instructed to apply maximal plantar flexion force against the card while the examiner applied a progressive horizontal pull at a constant speed of approximately 1 cm per second. The dynamometer was verified to start at zero before each measurement and was set to record the peak force reached, expressed in kilograms. Three trials were performed for each foot, with a

minimum rest interval of 30 s between repetitions. The order of assessment alternated between feet to facilitate muscle recovery. For each foot, the highest value among the three valid trials was used as the final score. All assessments were conducted in a laboratory setting with a firm, level surface. To standardize the friction between the foot support surface and the card used in the test, an A4-size sheet of paper was taped to the floor directly beneath the participant's foot (Figure 2). Previous research has demonstrated that PGT shows acceptable diagnostic performance for detecting hallux plantar flexor weakness. Specifically, when using a cutoff value of 2.6 kg, the sensitivity and specificity of the PGT for identifying reduced hallux plantarflexion strength were 80% and 79%, respectively [28].

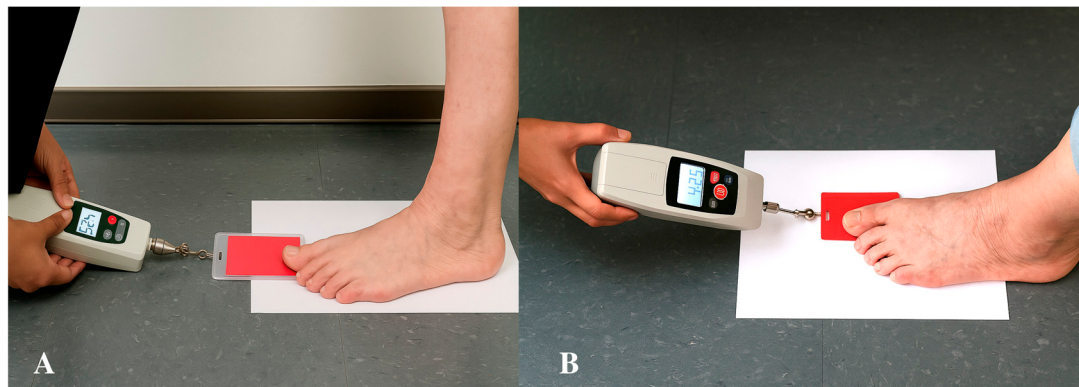


Figure 2. Paper Grip Test for the objective measurement of hallux plantar flexion strength: (A) lateral view and (B) superior view.

2.2.2. Physical Performance

Physical performance was assessed using the Short Physical Performance Battery (SPPB), a validated and reliable tool for evaluating physical function in both community-dwelling and clinical populations [29,30]. The SPPB comprises three timed subtests that assess balance, usual gait speed, and five times chair sit-to-stand (5-STs) [31]. Balance was evaluated by sequentially adopting three positions: feet-together stand, semi-tandem stand, and full-tandem stand, each held for 10 seconds. Gait speed was assessed by timing the participant over a 4 m straight course at their usual walking pace, using a high-precision digital stopwatch (Casio HS-70W-1DF, Tokyo, Japan) two trials were performed, and the fastest time was recorded. Lower limb strength was evaluated by timing the duration required to complete five consecutive sit-to-stand repetitions from a standard chair, starting at the initial lift and ending upon final seated position. The total SPPB score was obtained by summing the scores of each subtest, yielding a total score ranging from 0 to 12 points, with lower scores indicating poorer physical function [32].

2.2.3. Fall Risk

Participants' fall risk was evaluated through balance assessments, specifically the Single-Leg Stance (SLS) test and the Timed Up and Go (TUG) test. For the SLS test, the participants were instructed to lift one foot off the ground and maintain balance on the opposite foot for up to 30 s, with arms crossed over the chest and eyes looking straight ahead [33]. The time was recorded from the moment the foot left the ground until the first premature contact with the floor or loss of balance [34].

In the TUG test, the participants were instructed to rise from a chair with a backrest (without using the arms), walk three meters, turn 180°, return to the starting point, and sit down again. The time was recorded with a stopwatch from the initiation of movement until the participant was fully seated back in the chair [35]. The test was conducted on a flat surface, with visual markers delineating the walking path.

2.3. Statistical Analysis

The distribution of all variables was first assessed for normality using the Shapiro–Wilk test. Descriptive analyses were performed using mean and standard deviation (SD). Baseline characteristics of men and women were compared using an independent samples Student's *t*-test. To examine the relationship between the PGT and physical performance and fall risk variables, Pearson's correlation coefficient (*r*) was used. Correlation analyses were conducted both in the total sample and stratified by sex (females and males). The strength of the correlations was interpreted according to the following thresholds: very weak ($r = 0.00–0.19$), weak ($r = 0.20–0.39$), moderate ($r = 0.40–0.59$), strong ($r = 0.60–0.79$), and very strong ($r \geq 0.80$). Additionally, multiple linear regression analyses were performed to identify significant predictors of PGT performance (right and left foot) based on physical function and fall risk variables. All models were adjusted for sex and age to control for potential confounding effects. The goodness of fit was determined using the R^2 coefficient. A collinearity diagnosis was made for each variable in the regression models obtained, where variables with values less than 0.10 tolerance and values above 10.0 variance inflation factor (VIF) were eliminated. The level of significance was set at $p < 0.05$ for all analyses. All statistical analyses were conducted using GraphPad Prism software, version 8.0 (GraphPad Software, San Diego, CA, USA).

3. Results

Out of a total of 188 older adults evaluated, 89.3% were female ($n = 168$) and 10.6% were male ($n = 20$). Table 1 presents the sample characteristics, including age, body weight, height, and BMI. Specifically, women had a mean age of 72.2 ± 6.9 years (range: 60–93), while men had a mean age of 70.1 ± 5.8 years (range: 60–83). Baseline comparisons between men and women showed significant differences in body weight ($p = 0.021$) and height ($p < 0.001$). No significant differences were observed for age ($p = 0.412$) or BMI ($p = 0.198$). The descriptive results of the evaluations are presented in Table 2.

Table 1. Sample characteristics (mean and standard deviation).

	Females (n = 168)	Males (n = 20)	Total (n = 188)
Age (years)	72.03 ± 13.6	69.95 ± 5.77	71.81 ± 6.78
Body weight (kg)	71.00 ± 13.5	79.32 ± 17.68	71.00 ± 13.52
Height (m)	1.55 ± 0.09	1.68 ± 0.10	1.55 ± 0.09
BMI (kg/m ²)	29.44 ± 4.81	28.05 ± 4.04	29.44 ± 4.81

BMI: body mass index.

Table 2. Descriptive summary of the measured variables (mean and standard deviation).

	Females (n = 168)	Males (n = 20)	Total (n = 188)
PGT RF (kg)	6.58 ± 3.05	7.95 ± 3.68	6.76 ± 3.11
PGT LF (kg)	6.30 ± 2.88	7.39 ± 3.28	6.45 ± 2.91
Total score SPPB	9.63 ± 2.02	10.25 ± 2.07	9.70 ± 2.02
Balance (points)	3.88 ± 0.45	3.98 ± 0.11	3.89 ± 0.43
5-STs (points)	2.69 ± 1.17	2.80 ± 1.32	2.70 ± 1.18
Gait speed (points)	3.22 ± 0.93	3.50 ± 0.95	3.26 ± 0.94
TUG (s)	8.43 ± 2.50	9.02 ± 5.54	8.55 ± 2.97
SLS-R (s)	10.20 ± 6.28	10.52 ± 7.22	10.18 ± 6.37
SLS-L (s)	10.38 ± 6.30	11.08 ± 6.48	10.56 ± 6.30

PGT: Paper Grip Test; RF: right foot; LF: left foot; 5-STs: five times sit-to-stand test; TUG: Timed Up and Go; SLS-R: Single-Leg Stance Test—Right; SLS-L: Single-Leg Stance Test—Left.

Correlation analyses revealed several significant associations between PGT right foot (RF) performance and functional variables related to physical performance and fall risk,

both in the total sample and in sex-stratified analyses (Table 3). In the total sample ($n = 188$), PGT RF was positively correlated with total score SPPB ($p = 0.008$; $r = 0.178$), the gait speed component of the SPPB ($p = 0.002$; $r = 0.214$), SLS-Right ($p < 0.001$; $r = 0.316$), and SLS-Left ($p < 0.001$; $r = 0.397$). An inverse correlation was found with TUG execution time ($p < 0.001$; $r = 0.372$). In the male subgroup ($n = 20$), significant positive correlations were found between PGT RF and total score SPPB ($p = 0.048$; $r = -0.372$), the gait speed component of the SPPB ($p = 0.040$; $r = 0.397$), SLS-Right ($p = 0.030$; $r = 0.425$), and SLS-Left ($p = 0.010$; $r = 0.505$). A significant inverse correlation was observed with TUG ($p = 0.005$; $r = -0.559$). Among females ($n = 168$), significant associations were maintained between PGT RF and total score SPPB ($p = 0.040$; $r = 0.142$), gait speed component of the SPPB ($p = 0.010$; $r = 0.177$), SLS-Right ($p < 0.001$; $r = 0.309$), and SLS-Left ($p < 0.001$; $r = 0.376$). A significant inverse relationship was also found with TUG ($p < 0.001$; $r = -0.351$).

Table 3. Relationship between PGT RF and physical performance and fall risk variables.

	Females (n = 168)	Males (n = 20)	Total (n = 188)
Total score SPPB	$p = 0.040$; $r = 0.142$	$p = 0.048$; $r = 0.372$	$p = 0.008$; $r = 0.178$
Balance (points)	$p = 0.130$; $r = 0.089$	$p = 0.140$; $r = 0.259$	$p = 0.110$; $r = 0.093$
5-STST (points)	$p = 0.350$; $r = -0.030$	$p = 0.130$; $r = 0.267$	$p = 0.420$; $r = 0.015$
Gait speed (points)	$p = 0.010$; $r = 0.177$	$p = 0.040$; $r = 0.397$	$p = 0.002$; $r = 0.214$
TUG (s)	$p < 0.001$; $r = -0.351$	$p = 0.005$; $r = -0.559$	$p < 0.001$; $r = -0.372$
SLS-R (s)	$p < 0.001$; $r = 0.309$	$p = 0.030$; $r = 0.425$	$p < 0.001$; $r = 0.316$
SLS-L (s)	$p < 0.001$; $r = 0.376$	$p = 0.010$; $r = 0.505$	$p < 0.001$; $r = 0.397$

PGT, Paper Grip Test; RF, right foot; 5-STST, five times repeated chair sit-to-stand test; TUG, Timed Up and Go; SLS-R, Single-Leg Stance Test—Right; SLS-L, Single-Leg Stance Test—Left.

Similarly, correlation analyses between PGT left foot (LF) performance and physical performance and fall risk variables revealed several significant associations (Table 4). In the total sample ($n = 188$), PGT LF was positively correlated with total score SPPB ($p = 0.009$; $r = 0.175$), the gait speed component of the SPPB ($p = 0.002$; $r = 0.212$), SLS-Right ($p < 0.001$; $r = 0.317$), and SLS-Left ($p < 0.001$; $r = 0.351$). An inverse association was found with TUG execution time ($p < 0.001$; $r = -0.393$). In the male subgroup ($n = 20$), positive and significant correlations were found between PGT LF and total score SPPB ($p = 0.004$; $r = 0.577$), the gait speed component of the SPPB ($p = 0.006$; $r = 0.555$), SLS-Right ($p = 0.003$; $r = 0.587$), and SLS-Left ($p < 0.001$; $r = 0.658$). Additionally, a strong inverse correlation was detected between PGT LF and TUG ($p < 0.001$; $r = -0.696$).

Table 4. Relationship between PGT LF and physical performance and fall risk variables.

	Females (n = 168)	Males (n = 20)	Total (n = 188)
Total score SPPB	$p = 0.047$; $r = 0.125$	$p = 0.004$; $r = 0.577$	$p = 0.009$; $r = 0.175$
Balance (points)	$p = 0.110$; $r = 0.096$	$p = 0.060$; $r = 0.351$	$p = 0.090$; $r = 0.099$
5-STST (points)	$p = 0.470$; $r = -0.006$	$p = 0.120$; $r = 0.263$	$p = 0.210$; $r = 0.059$
Gait speed (points)	$p = 0.020$; $r = 0.156$	$p = 0.006$; $r = 0.555$	$p = 0.002$; $r = 0.212$
TUG (s)	$p < 0.001$; $r = -0.347$	$p < 0.001$; $r = -0.696$	$p < 0.001$; $r = -0.393$
SLS-R (s)	$p < 0.001$; $r = 0.282$	$p = 0.003$; $r = 0.587$	$p < 0.001$; $r = 0.317$
SLS-L (s)	$p < 0.001$; $r = 0.333$	$p < 0.001$; $r = 0.658$	$p < 0.001$; $r = 0.351$

PGT, Paper Grip Test; LF, left foot; 5-STST, five times sit-to-stand test; TUG, Timed Up and Go; SLS-R, Single-Leg Stance Test—Right; SLS-L, Single-Leg Stance Test—Left.

Among females ($n = 168$), PGT LF showed significant positive associations with total score SPPB ($p = 0.047$; $r = 0.125$), the gait speed component of the SPPB ($p = 0.020$; $r = 0.156$), SLS-Right ($p < 0.001$; $r = 0.282$), and SLS-Left ($p < 0.001$; $r = 0.333$). A significant inverse correlation was also found with TUG performance ($p < 0.001$; $r = -0.347$).

The multiple linear regression analyses showed that both TUG and SLS were significant predictors of PGT performance for both RF and LF (Table 5). The model for PGT RF explained 17% of the variance ($R^2 = 0.17$, $p < 0.001$). TUG was negatively associated with PGT RF ($\beta = -0.36$, $p < 0.001$; 95% CI: -0.54 to -0.17), whereas SLS-R was positively associated ($\beta = 0.10$, $p = 0.013$; 95% CI: 0.02 to 0.18).

Table 5. Multiple linear regression models for predicting PGT RF and PGT LF outcomes.

Test	R^2	Coefficient β	p -Value	95% CI
PGT RF	0.17		<0.001	
Intercept		9.51	<0.001	7.43 to 11.58
TUG (s)		−0.36	<0.001	−0.54 to −0.17
SLS-R (s)		0.10	0.013	0.02 to 0.18
PGT LF	0.20		<0.001	
Intercept		8.74	<0.001	6.97 to 10.52
TUG (s)		−0.34	<0.001	−0.50 to −0.18
SLS-L (s)		0.11	0.001	0.05 to 0.18

PGT, Paper Grip Test; RF, right foot; LF, left foot; SLS-R, Single-Leg Stance Test—Right; SLS-L, Single-Leg Stance Test—Left; 95% CI, 95% Confidence Interval.

Similarly, the model for PGT LF explained 20% of the variance ($R^2 = 0.20$, $p < 0.001$). TUG remained a negative predictor ($\beta = -0.34$, $p < 0.001$; 95% CI: -0.50 to -0.18), while SLS-L was positively associated with PGT LF ($\beta = 0.11$, $p = 0.001$; 95% CI: 0.05 to 0.18). The physical performance variables included in the models did not show statistically significant associations with PGT outcomes. Additionally, age and sex were included as covariates in all models, but neither significantly contributed to the prediction of PGT RF or LF performance.

4. Discussion

The present study revealed a significant relationship between hallux plantar flexion strength, assessed using the PGT, and both physical performance and fall risk assessments in older adults. Specifically, a positive correlation was observed between PGT values for both feet and the total SPPB score, particularly with the gait speed component. Additionally, significant associations were identified with SLS for both feet, and an inverse relationship was found with TUG execution time. Beyond these correlations, multiple linear regression models revealed that both the TUG and the ipsilateral SLS significantly predicted PGT performance, underscoring a functional link between hallux strength and postural control demands. Importantly, the variables that explained PGT performance were those traditionally related to fall risk, rather than general physical performance measures, reinforcing the hypothesis that the PGT may serve as a clinically relevant indicator for fall risk in older adults. However, the explained variance was modest (17–20%), suggesting that hallux strength is only one of several factors influencing physical performance and fall risk. In this sense, the PGT should be interpreted as a complementary screening tool within the broader framework of geriatric assessment, which usually also includes evaluations such as gait speed, balance tests, and muscle strength assessments (e.g., handgrip dynamometry).

The observed correlation between hallux plantar flexion strength and the overall SPPB score is consistent with the findings of Mansi et al. [20] and Chatzistergos et al. [23], who identify this variable as a clinically relevant indicator of physical performance in older adults. From a biomechanical perspective, hallux strength actively contributes to the efficient functioning of the windlass mechanism, whereby the first metatarsophalangeal joint generates tension in the plantar fascia, elevates the medial longitudinal arch, and enables the foot to act as a rigid lever during the propulsive phase of gait [36,37]. This

functional sequence not only optimizes force transmission during toe-off but also activates an ascending kinematic chain characterized by midfoot supination and external rotation of the tibia and femur [37]. These movements contribute to better lower limb alignment and facilitate efficient center of mass translation [37]. In this context, the hallux plantar flexors not only stabilize the first toe against the ground and control its motion, but also reinforce plantar tissue tension, promoting more efficient gait mechanics [36]. Therefore, their role extends beyond local function, positioning them as key contributors to gait biomechanics and functional mobility in older adults. Within the framework of the SPPB, which includes gait speed and postural transition tasks, these biomechanical effects are fundamental. Proper activation of the windlass mechanism, supported by sufficient hallux strength, improves foot rigidity, reduces double-support time, and increases propulsive efficiency, all of which are directly related to enhanced physical performance [36].

Along the same lines, Menz, Morris, and Lord (2006) demonstrated that greater hallux plantar flexor strength, as measured by the PGT, was associated with better performance in functional tasks such as chair rise and particularly walking [28]. In their regression analyses, this variable alone explained up to 59% of the variance in these performance tests among older adults. Furthermore, participants who failed to hold the paper during the test exhibited greater postural sway and slower gait speed, findings directly associated with increased fall risk and reduced functional capacity [28].

When examining the SPPB components individually, a significant correlation was identified between hallux plantar flexion strength and gait speed, measured in seconds. This finding aligns with that of Yan et al. (2023), who reported that greater hallux strength was associated with superior performance in dynamic tasks, particularly walking, by improving weight transfer efficiency and optimizing the propulsive phase [38]. In their study, participants with higher hallux strength exhibited significantly faster gait times and lower frailty indices, reinforcing the clinical value of this variable as a functional marker. These findings support the notion that hallux plantarflexion strength should not be regarded merely as a peripheral muscular capacity, but rather as a biomechanically integrated determinant of locomotor performance, especially relevant for mobility and disability prevention in older adults.

It is noteworthy that when stratifying the analyses by sex, the correlations between hallux plantar flexion strength and physical performance variables remained significant in both men and women; however, the strength of the associations was consistently higher in the male subgroup. Men exhibited moderate-to-strong correlations between PGT performance and the SPPB total score, gait speed, TUG, and SLS time. While these findings should be interpreted with caution due to the smaller male sample size ($n = 20$), they suggest a potentially more pronounced role of hallux strength in determining functional performance among older men. This sex-specific pattern aligns with previous evidence indicating differential neuromuscular adaptation and functional decline trajectories in aging populations, and it underscores the importance of considering sex as a biological variable in future investigations on foot function and fall risk in older adults [22].

Another key result from this study was the significant inverse relationship between hallux plantar flexion strength and TUG performance, indicating that greater strength in this region is associated with superior functional capacity and lower fall risk. Consistently, Kamasaki et al. (2024) found similar results between toe flexor strength and TUG times in older adults with pronated and supinated feet, suggesting that hallux plantar flexor capacity supports improved dynamic mobility [39].

The present study also identified significant associations between PGT scores and both right and left SLS times. This relationship is supported by evidence showing that intrinsic foot muscles are activated proportionally to increasing postural demands, as occurs

during unipedal support by stabilizing the forefoot and medial longitudinal arch under compressive loads [40]. In addition, Ridge et al. [41] reported that greater hallux muscle strength is associated with significantly reduced center-of-pressure displacement during single-leg balance tasks, reflecting greater ability to maintain stability under perturbations.

This stabilizing function enhances postural control and provides a more rigid and efficient base of support, facilitating longer and more controlled single-leg balance performance [41].

In contrast, 5-STs did not show a significant association with hallux plantar flexion strength. This may be attributed to the biomechanical nature of the test, which primarily requires hip and knee extensor strength, with minimal direct involvement of the hallux. Nevertheless, the absence of an association in this specific task does not diminish the functional importance of intrinsic foot musculature in other essential activities related to autonomy in older age. Weakness in this region may precede functional decline, while its preservation or strengthening may represent a valuable target for preventive interventions. These findings are not only consistent with the previous international literature but also but also contribute novel insights into the clinical utility of hallux plantar flexion strength and the PGT in Latin American older adults, a population that remains underrepresented in previous research. Given its simplicity, low cost, and strong association with critical functional variables, this measure could be integrated as a screening tool in community and clinical settings, contributing to prevention strategies for functional decline and falls in older adults. Furthermore, this evidence highlights the need for future studies aimed at establishing normative reference values and exploring the clinical implications of hallux strength assessment in Latin American older populations.

4.1. Limitations and Strengths

This study presents several limitations that should be considered when interpreting the results. First, the cross-sectional design prevents the establishment of causal relationships between hallux plantar flexion strength and the functional variables analyzed. Although significant associations were identified, it is not possible to determine whether reduced hallux strength precedes functional decline or is a consequence of it. Second, despite performing stratified analyses by sex, the markedly reduced number of male participants ($n = 20$) limits the robustness of these findings. Consequently, sex-specific results should be considered exploratory and interpreted with caution. Third, the sample was recruited from a specific community setting, which may limit the generalizability of the findings to other populations of older adults with different functional, clinical, or sociocultural characteristics. Moreover, the sample presented a marked imbalance between male and female participants, which may have affected the stratified analyses and limited the robustness of sex-specific conclusions. Fourth, although the PGT is an accessible and low-cost tool, its application may be influenced by factors such as the participant's understanding of instructions, the examiner's level of experience, or joint conditions affecting the first toe, underscoring the need to standardize administration procedures and interpretation criteria. Finally, the sampling method was non-probabilistic by convenience, which, combined with the inclusion of older adults with heterogeneous functional levels, may limit the extrapolation of the findings and reduce their representativeness of the broader population.

Despite these limitations, the findings of the present study offer important clinical implications and practical applications. In particular, the finding that hallux strength is associated with key indicators of physical performance and fall risk positions this variable as a potential peripheral functional marker, easily assessable in both clinical and community settings. A notable strength of this study is the use of a digital dynamometer-based measurement device, which allowed for objective and standardized quantification of hallux

muscle strength, reducing subjective bias and increasing the precision of the results. Given the simplicity, low cost, and applicability of the PGT, its incorporation is recommended in routine assessments of the foot–ankle complex, especially in older adults who appear functionally independent but may present underestimated deficits that could compromise their mobility or balance.

4.2. Future Applications

From an interventional perspective, future research should explore specific strategies aimed at strengthening the plantar flexor muscles of the hallux, given their relevance in functional tasks such as gait, single-leg balance, and postural transitions. Targeted exercises for the intrinsic foot musculature, such as short foot training, electromyographic biofeedback techniques, or progressive elastic resistance programs, have shown preliminary evidence of efficacy in improving hallux strength, balance, and gait pattern quality in older adults [41,42]. These interventions, in addition to being safe and accessible, could be integrated as key components of preventive or functional rehabilitation programs in primary care to preserve mobility, extend autonomy, and reduce the incidence of falls in this population.

5. Conclusions

Our findings indicate that intrinsic foot musculature—particularly hallux plantar-flexor strength—is associated with key indicators of physical function and fall risk in community-dwelling older adults (SPPB, TUG, and SLS). While these relationships were statistically significant, their magnitude was modest, and the regression models explained a limited proportion of variance ($\approx 17\text{--}20\%$), suggesting that hallux strength is one of several contributors to mobility and balance, and underscoring the need for further research to identify additional physiological, biomechanical, and psychosocial factors involved. In this sense, the PGT should be interpreted as a complementary, accessible screening tool within a multidimensional geriatric assessment, rather than a stand-alone determinant. Given its simplicity and low cost, incorporating hallux strength assessment may help flag individuals at potential risk of mobility decline and inform early, pragmatic interventions. Future longitudinal and interventional studies—ideally with more balanced samples—are warranted to confirm predictive validity for falls, establish context-specific reference values and cutoffs in Latin American populations, and determine whether targeted strengthening of hallux musculature translates into clinically meaningful improvements in mobility and quality of life.

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was explicitly stated that, in the event of any discomfort or muscle pain during or after the physical assessments, participants were required to notify the research team in order to initiate appropriate clinical follow-up and safeguard their well-being.

Informed Consent Statement: All participants provided written informed consent prior to participation.

Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

PGT	Paper Grip Test
SLS	Single-Leg Stance Test
SPPB	Short Physical Performance Battery
TUG	Timed Up and Go Test
5-STST	Five times sit-to-stand test

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