# The physical determinants of maximal jumping time of flight in elite trampolining

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# Abstract

Time of flight (ToF) is an objective scoring component of elite trampolining, assessed in training by maximal jump tests. The aim of this study was to assess the relationship between physical floor based performance meaures and 20-maximum ToF. Thirty two elite level gymnasts (13 senior; 19 junior) performed a battery of floor based tests and a 20-maximum jump test. Floor based tests included cycling peak power output, reactive strength index (RSI), unloaded countermovement jumps (CMJ), and loaded CMJ's to construct a load-velocity profile for prediction of theoretical maximum force (CMJ $F_0$). Very large and large, positive bivariate relationships were observed between CMJ $F_0$ and ToF for the seniors ($r = 0.85$) and juniors ($r = 0.56$), respectively. Very large, positive bivariate relationships were observed between CMJ height and total ToF for both seniors ($r = 0.74$) and juniors ($r = 0.77$). Step-wise multiple regression analyses revealed CMJ $F_0$ predicted 72% of ToF variability between seniors, and CMJ height (59%), 10 to 5 RSI (13%), and CMJ $F_0$ (10%) predicting 82% of ToF variability between juniors. This suggests CMJ $F_{0,}$ lower limb maximal isometric capabilities, and CMJ height are important floor based predictors of maximal ToF in elite gymnasts.

**Keywords:** Performance, elite athlete, trampolining, load-velocity, countermovement jump

## Highlights

- Trampolining is an Olympic sport, however the determinants of maximal jumping (critical component of the overall score) are poorly understood.
- The relationship between floor based performance test metrics and 20-max time of flight performance was explored.
- Theoretical lower limb maximal isometric capabilities, as calculated by force velocity extrapolation, and CMJ height are important floor based tests and predictors of maximal ToF in senior and junior elite trampoline gymnasts.
- This information can be used to target specific, trainable physical qualities that can improve the determining factors such as lower limb maximal isometric force, and therefore have the potential to influence maximal ToF performance.

## Introduction

Elite level trampoline competition requires gymnasts to perform maximal jumps to gain, and maintain, vertical displacement (jump height) in order to execute technical skills. Enhancing maximal jumping ability is important for two reasons: 1) time of flight (ToF) is an objective constituent part of the trampoline scoring system, and, 2) achieving higher ToF permits more time to execute the required technical skills. ToF represents the time spent in the air from the moment the gymnast leaves the trampoline bed until they make contact again. The ToF scoring component has been reported to have a determining influence on elite level competition standings (Harden & Earnest, 2015; Heinen & Krepela, 2016) albeit before the introduction of the HD scoring component, and understanding the physical qualities that underpin ToF performance could help direct appropriate training interventions. ToF is commonly measured in trampoline training using maximal jump tests, such as the 20-maximum (20-max) using the same method for ToF assessement as used in elite level competition. The 20-max is a commonly used monitoring tool to assess maximal ToF performance and has been shown to be highly reliable (Dyas et al., 2021).

Due to the height at which gymnasts perform on the trampoline and elastic nature of the surface, it is difficult to ascertain direct physical measures from gymnasts during trampolining. Wider trampoline training often involves off bed performance tests as surrogate measures to better understand the physical attributes of trampoline gymnasts. However, the relationship between the use of off bed performance tests and maximal trampoline is poorly understood. The biomechanics of the trampoline jump provides insight into the possible importance of different physical qualities in determining maximal trampolining jump ability. Trampoline bouncing shares some similarities with the ‘countermovement’ jump (CMJ), with triple flexion of the hip, knee and ankle joints, followed by bilateral explosive triple extension of the hip, knee and ankle joints (Harden & Earnest, 2015). However, there are important differences between the CMJ and trampoline jumping. Kinematic measures of maximal trampoline jumping highlight that during the contact phase only knee and hip extension is observed (Rupf & Chapman, 2013). This suggests that knee and hip flexion occurs exclusively in the downward aerial phase prior to contact with the bed, with hip and knee angles on contact reported to be between 25°-40° and 20°-40°, respectively (Qian et al., 2020; Rupf & Chapman, 2013). At the end of the contact phase, hip and knee angles were both reported to be less than 10° (Rupf & Chapman, 2013). Average contact times of 0.32 s have been reported for the 20-max jump test (Dyas et al., 2021) suggesting a relatively long contact time in which the gymnast must maintain knee and hip flexion in a quasi-isometric manner, and subsequently forcibly extend through a small range of motion. In addition, the peak forces experienced during CMJ (1991 ± 338 N; Nuzzo et al., 2008) are considerably lower than experienced by gymnasts during maximal trampoline jumping 7757 ± 1381 N (Dyas et al., 2021). The elastic nature of the trampoline surface and force differences is the likely explantion for the different jumping mechanics on-bed compared to on-land. Despite the unique kinematics of trampoline jumping, little is known about the physical characteristics that determine maximal trampoline jumping ability in elite gymnasts.

It is well-accepted that measures of strength correlate with on-land jumping performance. Positive interactions have been reported between relative lower body muscular strength, as measured by a one-repetition maximum squat, and vertical jump performance (Nuzzo et al., 2008). In addition, training programmes targeting measures of maximal leg strength have, in turn, resulted in increased vertical jump height (Stone et al., 2003). A limited number of off-bed physical performance tests have been previously assessed in non-elite gymnasts with a view to providing insight into the key physical determinants of on-bed trampoline performance. A strong positive correlation has been reported between a one repetition maximum leg press and the maximum height jumped on a trampoline (r = 0.80) during a maximal jump test (Briggs, 2014), in a non peer reviewed thesis. However, no correlation (r = 0.56) was observed between off-bed CMJ performance and trampoline jump height (Briggs, 2014). This indicates isoinertial strength could be an important physical determinant of maximal trampoline jumping, and that off-bed and on-bed jump performance might be influenced by different factors. Off-bed jumping performance, such as the drop jump, requires a relatively short (0.25 s) stretch shortening cycle (SSC) action, and full extension of the ankle, knee and hip on take-off (Haff & Nimphius, 2012; Marques, 2010). In contrast, as previously highlighted, trampoline jumping requires forceful maintenance of knee and hip flexion on contact with the bed, a subsequent shorter range of extension, and a longer contact time as measured using the HDTS system (0.32s; Dyas et al., 2021). It is likley that trampoline jumping requires a different profile of physical qualities to off-bed jumping, but this conclusion is limited by the lack of data on a range of physical performance tests to measure specific strength qualities (e.g. maximum isometric strength, reactive strength), and a limited study of 8 non-elite trampoline gymnasts, thus further research is warranted.

The primary aim of the study was to explore the relationship between off-bed physical performance measures and maximal ToF in senior and junior elite level trampoline gymnasts. Identification of such indices could be used by practitioners and coaches as a means to understand physical qualites important for trampoline performance and as monitoring for athletic development.

## Materials and methods

### *Subjects*

Thirty two trampoline gymnasts were recruited from the British Gymnastics National trampoline squads. For the analysis, the gymnasts were split into two groups, senior (over 17 years, eligible for senior competition) and junior (under 17 years). The senior group (n = 13 (females = 6; males = 7); age = 21 ± 5 years; stature = 173.8 ± 9.3 cm; mass = 68.2 ± 7.5 kg), included gymnasts who had participated at the Olympic Games, World or European Championships, or competed internationally at age group level. The junior group (n = 19 (females = 11; males = 8); age = 15 ± 1 years; stature = 163.1 ± 6.3 cm; mass = 54.7 ± 9.8 kg) included gymnasts that had competed internationally at age group level. The study was approved by the Northumbria University Research Ethics Committee, in accordance with the Declaration of Helsinki. Written informed consent was provided by all participants, and assent by parents and/or guardians, where appropriate.

### *Design*

A familiarisation session that was identical to the main trial was conducted 24-72 hours prior to testing. Participants were instructed to refrain from caffeine on the test day and arrive in a fed and euhydrated state. Following stature and body mass measures, a 10-minute warm-up was performed on a WattBike Pro or Trainer (Wattbike, 2020), at an RPE of 5, on a 0-10 scale (Borg, 1998). Participants performed two seated 6-second peak power output (PPO) tests on a WattBike, followed by a series of jump tests: a 10 to 5 repeated jump test, three single leg drop jumps on each leg, and three unloaded CMJ's followed by three loaded CMJ's at three incremental loads. A 2-minute rest period was observed between all jump based tests, with a further 5-minute rest period prior to the 20-max trampoline jump test.

## ***Methodology***

### *Seated 6-second peak power output test*

Participants performed two maximal 6-second PPO tests from a stationary seated start (each seperated by 2 minutes). Strong verbal encouragment and appropriate cues were provided throughout the test, with participants instructed to remain seated throughout. PPO and relative PPO data were calculated by the ergometer. The Wattbike ergometer has been shown to measure power output with acceptable accuracy (Hopker et al., 2010). All participants exhibted PPO measures with less than 5% difference between efforts, therefore mean data from the two efforts was used for analysis.

### *Jump testing*

All jump testing was peformed on ForceDecks FD4000 Dual Force Platforms (ForceDecks, London, UK), with a sampling frequency of 1000 Hz and interfaced with software for offline analysis (ForceDecks Performance Technologies Software, London, UK). Take-off was defined as the time when total vertical force fell below 30 N body mass threshold, and landing defined as he point when total vertical force rises above 30N.

### *Ten to Five Repeated Jump Test*

Participants performed a 10 to 5 repeated jump test (Stratford et al., 2020) for measurement of reactive strength index (RSI), by performing 11 maximal vertical rebound jumps, with the first jump excluded as it did not involve the SSC. They aimed to jump as high as possble, maintain the shortest ground contact time and keep hands on hips. Up to five practice jumps were permitted. Jump height (from flight time) and contact time were recorded for each jump. RSI was calculated for each of the five highest jumps, all of which had a contact time of less than 0.25 s (flight time divided by contact time). An average of the five calculated RSI measures was taken to obtain a total RSI for the ten to five repeated jump test.

### *Single Leg Drop Jumps*

Participants then performed three single leg drop jumps on each leg from a box of 30 cm height with 15 s rest periods observed between jumps. They aimed to jump as high as possible, retain the shortest ground contact time and keep hands on hips. ForceDecks analysis software calculated measures of contact time and jump height (from flight time) for each jump. There was less than 5% difference between metrics for each trial, therefore average RSI for the three drop jumps on each limb was used for analysis.

### *Countermovement Jumps*

A 20 N offset measured from body mass prior to the jump was used to define the start of the jump. The end of the eccentric (and start of the concentric) phase was defined as the minimum displacement that was equal to zero velocity. Push-off distance was calculated as the difference between the extended lower limb length and initial squat height, in line with previous work (Jiménez-Reyes et al., 2017). Participants aimed to retain the same squat depth for each CMJ and jump as high as possible. They performed three unloaded CMJ's with 30-second rest period between efforts, and three maximal jumps at each load wearing a weighted jacket. Junior participants used loads of 4, 8 and 12 kg. Senior participants used loads of 8, 16, and 24 kg. The final CMJ with additional load resulted in a jump height of approximately 10 cm (Morin & Samozino, 2016). A 2-minute rest period followed each weighted CMJ.

Trials with the greatest jump height for each condition were used for analysis. For the unloaded CMJ's, ForceDecks analysis software calculated automatic measures of jump height (from flight time), peak concentric force, concentric impulse, peak eccentric force and eccentric impulse. Predicted force-velocity relationships were determined by least-squares linear regressions (Rahmani et al., 2001; Samozino et al., 2012). Predicted force, velocity, and power data from the best trial at each load was determined by averaging data from the entire push-off phase of each jump. Force-velocity curves were extrapolated to obtain $F_0$ (theoretical maximal force at null velocity) and $v_0$ (theoretical maximal velocity at which lower limbs can extend under zero load), which respectively correspond to the intercepts of the force-velocity curve with the force and velocity axis. $P_{MAX}$ (maximal power output against different loading conditions) values were determined as: $P_{MAX} = F_0 \times v_0/4$ (Samozino et al., 2012). Data from the participants familiarisation trial were compared to the test trials for force-velocity profiles to assess the repeatability of the predicted measures, specifically the typical error and coefficient of variation with 95% confidence intervals. For $F_0$, typical error = 0.27 (0.13 – 0.21) and coefficient of variation = 8.6% (6.8% - 11.5%). For $V_0$, typical error = 0.61 (0.39 – 0.81) and coefficient of variation = 9.3% (7.4% - 12.6%).

*20-Maximum Trampoline Jump Test*

Following a 5-minute rest period, gymnasts performed a 20-max trampoline jump test on a competition standard trampoline (Eurotramp, Premium 4×4, Germany) connected to an FIG approved Eurotramp HDTS system (Eurotramp, Germany), that calculated total ToF and contact time for the 20-max jump test. The total ToF metric is the sum total of ToF of each of the 20 consecutive jumps performed during the 20-max test, with contact time omitted to give only the total time gymnasts spend in the air. The HDTS system was connected to the base of the trampoline, and interfaced to a laptop containing Eurotramp ToF analysis software (Qira 1.03, Eurotramp, Germany). Prior to use, the HDTS system is calibrated and adjusts its' state to the calibration if necessary (Eurotramp Trampoline, 2021; Ferger et al., 2019). Force plates under each of the four feet of the trampoline, produce a deformation of the sensor causing a change in light intensity, whilst optoelectronic sensors measure normal force in a one-dimensional plane (Ferger & Hackbarth, 2017). Scanning is performed at 2 kHz (internally 50 kHz, mean average formation over 25 values), data is provided every 0.5 ms and the sensor has a resolution of less than 0.5 N at an accuracy of 1% (Ferger et al., 2019). Participants started from a static position in the centre of the bed and performed 20 maximal straight jumps, which they all commonly perform during training sessions.

### *Statistical Analysis*

All data are presented as mean ± SD. Pearson's product-moment correlations (r) were employed to examine the relationship between measures of physical function and the criterion variable (Total ToF). The following criteria were adopted to interpret the magnitude of the relationship between the test variables: 0.1-0.3 small, 0.3-0.5 moderate, 0.5 to 0.7 large, 0.7 to 0.9 very large and >0.9 nearly perfect (Hopkins, 2015). Variables that were significantly correlated ($r > 0.5$) with the ToF variables were included in a step-wise regression analysis to predict total ToF. Between group comparisons were conducted using independent t-tests. Effect sizes (Cohen's d) were calculated to establish the magnitude of between-group differences using the following classification: <0.2, trivial; 0.2-0.59, small; 0.6-1.19 moderate; 1.2-1.99, large; 2.0-4.0, very large (Hopkins et al., 2009). All statistics were calculated using SPSS (IBM Corp. Version 26.0. Armonk, USA). No significant differences were identified between off bed performance tests and 20-max total ToF, when the data was split by sex (males and females).

## Results

For the senior and junior gymnasts, the average ± SD and range (maximum and minimum) of the performance and physical measures are presented in Table 1.

**Table 1.** 20-max trampoline gymnastics performance and physical measures for thirty two elite gymnasts. Data are mean ± SD and range for minimum to maximum values.

| | **Senior (n = 13)** | | **Junior (n = 19)** | | | |
|---|---|---|---|---|---|---|
| **Variable** | **Mean ± SD** | **Range (max-min)** | **Mean ± SD** | **Range (max-min)** | **p value** | **Effect size** |
| **20-max total ToF (s)** | 32.9 ± 1.6 | 35.8-30.3 | 30.2 ± 1.4 | 33.2-28.2 | < 0.001 | 1.78 |
| **20-max average contact time (s)** | 0.33 ± 0.01 | 0.34-0.30 | 0.32 ± 0.02 | 0.34-0.27 | 0.123 | 0.63 |
| **Cycle PPO (W·kg$^{-1}$)** | 13.6 ± 2.6 | 17.6-9.2 | 11.5 ± 1.8 | 14.4-8.0 | < 0.05 | 0.94 |
| **10 to 5 RSI (m·s$^{-1}$)** | 1.81 ± 0.41 | 2.43-1.07 | 1.36 ± 0.4 | 2.26-1.01 | < 0.05 | 1.11 |
| **Left leg RSI (m·s$^{-1}$)** | 0.58 ± 0.11 | 0.79-0.39 | 0.46 ± 0.13 | 0.70-0.25 | < 0.05 | 1.00 |
| **Right leg RSI (m·s$^{-1}$)** | 0.62 ± 0.17 | 0.96-0.45 | 0.45 ± 0.12 | 0.74-0.26 | < 0.05 | 1.16 |
| **CMJ height (m)** | 0.41 ± 0.07 | 0.52-0.32 | 0.31 ± 0.06 | 0.46-0.22 | < 0.001 | 1.53 |
| **CMJ peak concentric force (N·kg$^{-1}$)** | 25.9 ± 3.2 | 29.9-19.7 | 23.6 ± 3.0 | 29.2-19.0 | < 0.001 | 0.74 |
| **CMJ concentric impulse (N·kg$^{-1}$·s)** | 2.5 ± 0.4 | 3.2-1.7 | 2.3 ± 0.3 | 2.8-1.5 | 0.132 | 0.57 |
| **CMJ peak eccentric force (N·kg$^{-1}$)** | 24.3 ± 2.8 | 29.0-19.1 | 16.9 ± 5.4 | 25.5-10.2 | < 0.001 | 1.72 |
| **CMJ eccentric impulse (N·kg$^{-1}$·s )** | 0.49 ± 0.09 | 0.61-0.32 | 0.56 ± 0.12 | 0.91-0.36 | 0.074 | 0.66 |
| **CMJ $F_0$ (N·kg$^{-1}$)** | 45.8 ± 10.5 | 64.1-32.7 | 33.3 ± 11.6 | 60.6-20.6 | < 0.001 | 1.13 |
| **CMJ $v_0$ (m·s$^{-1}$)** | 3.1 ± 0.7 | 4.6-2.4 | 2.9 ± 0.6 | 3.7-1.8 | 0.290 | 0.31 |
| **CMJ $P_{MAX}$ (W·kg$^{-1}$)** | 31.6 ± 10.7 | 61.5-21.2 | 21.9 ± 7.6 | 44.0-9.5 | < 0.05 | 1.05 |

Abbreviations: 20-max (20-maximum);Time of flight (ToF); PPO (peak power output); RSI (reactive strength index); Countermovement jump (CMJ); theoretical maximal force at null velocity ($F_0$); theoretical maximal velocity at which lower limbs can extend during 1 extension under zero load ($v_0$); $P_{MAX}$ (maximal power output against different loading conditions).

Table 2 shows the bivariate correlations between measures of physical function and total ToF for the senior and junior gymnasts.

**Table 2.** Bivariate relationships (r) for a range of physical measures and the criterion measure, Total Time of Flight, in elite senior (n = 13) and elite junior (n = 19) trampoline gymnasts.

| **Variable** | **Senior Total ToF (r)** | **Junior Total ToF (r)** |
|---|---|---|
| **Cycle PPO ($W \cdot kg^{-1}$)** | 0.77** | 0.52* |
| **10 to 5 RSI ($m \cdot s^{-1}$)** | 0.03 | 0.63** |
| **Left leg RSI ($m \cdot s^{-1}$)** | 0.22 | 0.48 |
| **Right Leg RSI ($m \cdot s^{-1}$)** | 0.48 | 0.49 |
| **CMJ height (m)** | 0.74** | 0.77** |
| **CMJ peak concentric force ($N \cdot s^{-1}$)** | 0.19 | 0.14 |
| **CMJ concentric impulse ($N \cdot kg^{-1} \cdot s$)** | 0.58* | 0.04 |
| **CMJ peak eccentric force ($N \cdot s^{-1}$)** | 0.31 | 0.60** |
| **CMJ eccentric impulse ($N \cdot kg^{-1} \cdot s$)** | -0.40 | 0.09 |
| **CMJ $F_0$ ($N \cdot kg^{-1}$)** | 0.85** | 0.56* |
| **CMJ $V_0$ ($m \cdot s^{-1}$)** | 0.39 | 0.16 |
| **CMJ $P_{MAX}$ ($W \cdot kg^{-1}$)** | 0.51 | 0.14 |

Abbreviations: 20-maximum (20-max);time of flight (ToF); peak power output (PPO); reactive strength index (RSI); countermovement jump (CMJ); theoretical maximal force at null velocity ($F_0$); theoretical maximal velocity at which lower limbs can extend during 1 extension under zero load ($v_0$); maximal power output against different loading conditions ($P_{MAX}$). *$p < 0.05$; **$p < 0.01$.

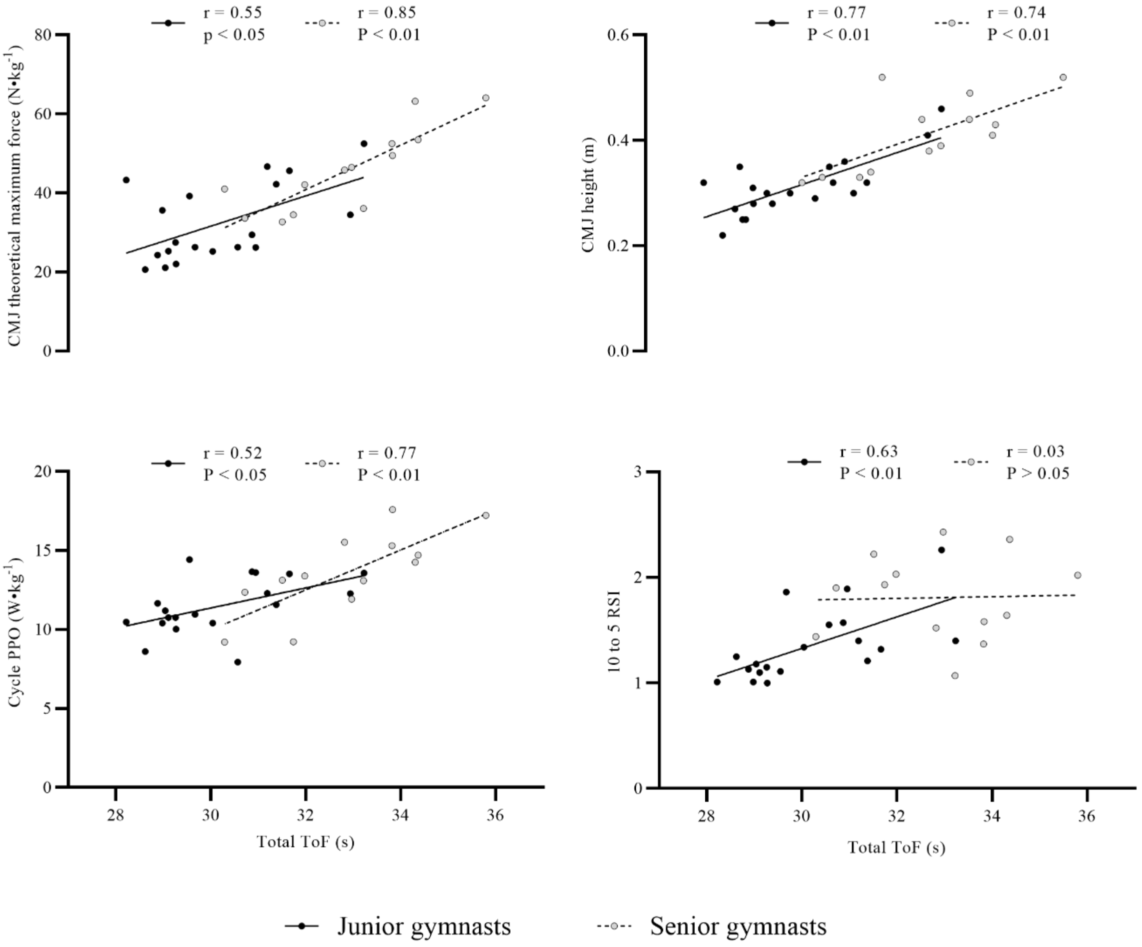

**Figure 1.** Scatter plots showing the relationships between 20-max total ToF and significant physical measures that were entered into the regression analysis: (a) countermovement jump theoretical maximal force realative to body mass, (b) countermovement jump height, (c) cycle peak power output realative to body mass, and (d) 10 to 5 RSI.

For the senior gymnasts, very large positive correlations were found between total ToF and CMJ $F_0$ ($r = 0.85$, $p < 0.01$), cycle PPO ($r = 0.77$, $p < 0.01$) and CMJ height ($r = 0.74$, $p < 0.05$). Other variables ranged from small to large correlations. Subsequently, stepwise multiple regression analysis using the four significant variables from the bivariate correlations (CMJ $F_0$, cycle PPO, CMJ height, CMJ concentric impulse), found 72% of the variability in total ToF between senior gymnasts ($F_{(1,11)} = 38.48$, $p < 0.01$) was explained by CMJ $F_0$.

For the junior gymnasts, very large positive correlations were found between total ToF and CMJ height ($r = 0.77$, $p < 0.01$). Large, positive correlations were found between total ToF and 10 to 5 RSI ($r = 0.63$, $p < 0.01$), CMJ peak eccentric force ($r = 0.60$, $p < 0.01$), CMJ $F_0$ ($r = 0.56$, $p < 0.05$) and cycle PPO ($r = 0.52$, $p < 0.05$). Subsequently, stepwise multiple regression analysis using the five significant variables from the bivariate correlations (CMJ height, 10 to 5 RSI, CMJ peak eccentric force, CMJ $F_0$ and CMJ PPO), found 82% of the variability in total ToF between junior gymnasts ($F_{(3,15)} = 22.95$, $p < 0.01$) was explained by CMJ height (59%), 10 to 5 RSI (13%) and CMJ $F_0$ (10%).

## Discussion

The primary aim of the study was to assess the relationship between floor based physical performance measures and maximal ToF, using a 20-max ToF test in senior and junior elite level trampoline gymnasts. CMJ height showed very large positive correlations with 20-max total ToF for both senior and junior gymnasts. CMJ $F_0$ alone explained 72% of the variability in ToF between senior gymnasts. Whereas, CMJ height, 10 to 5 RSI and CMJ $F_0$, explained 82% of variability in 20-max total ToF between junior gymnasts. To the best of knowledge, this is the first study to assess the relationship between a variety of physical performance tests and maximal ToF as determined by the 20-max jump test in elite level gymnasts.

In senior level gymnasts, 20-max total ToF was determined largely by CMJ $F_0$. A trend also observed, to a lesser extent, with the junior gymnasts. $F_0$, $V_0$ and $P_{MAX}$, embody the maximal mechanical capabilities of the lower limbs to generate external force, power output, and extension velocity, respectively (Samozino et al., 2012). A significant correlation has been reported between one repetition maximum leg press performance and maximum jump height during a maximal trampoline jump test ($r = 0.80$),(Briggs, 2014) suggesting maximum isoinertial strength is of importance during a maximal trampoline jump. CMJ $F_0$ describes the maximal isometric force output of the lower limbs. Conceptually, maximising energy transferral from the gymnast to the bed to achieve maximal ToF could explain why $F_0$ was identified as the most important determinant in this study and hence the importance of maximal strength in these gymnasts. The quadriceps and gluteus maximus have been suggested to play important roles in maximising energy transferral on the bed (Qian et al., 2020). $F_0$ as calculated by loaded CMJ's is highly determined by maximal isometric strength and size of the knee extensors (Morales-Artacho et al., 2018). As previously described, the portion of the CMJ action which takes place when the gymnast is in contact with the bed is lower limb extension. It could be suggested that the same physical variables underpinning CMJ $F_0$, the isometric strength of the lower limb musculature and size of the knee extensors, may also contribute to maximising ToF on the trampoline.

The CMJ is a commonly employed monitoring tool in trampoline gymnastics. This study found a very strong correlation between CMJ height and total ToF for both junior and senior groups. CMJ height values for the senior level gymnasts (0.41 ± 0.07 cm) were comparable to values previously reported in fifteen national level male trampoline gymnasts (0.40 ± 0.12 cm), (Jensen et al., 2013). However, it has previously been reported that CMJ height did not correlate with maximal jump height achieved on the trampoline during a maximal jump test (Briggs, 2014). The contrast in findings could be due to methodological differences, as participants were non-elite gymnasts and maximal trampoline jump height from the single greatest jump was used as the performance variable (Briggs, 2014), compared to total ToF used in this study over 20 jumps.

We observed a very strong correlation between CMJ height and total ToF, for both groups of gymnasts, suggesting gymnasts that jump higher on the floor also exhibit greater ToF on the trampoline during a maximal jump test. This suggests there may be similarities between jumping on the floor and the trampoline, regardless of differences between the nature of the surfaces, and the kinematics of the jumps.The CMJ on the floor is perhaps the most biomechanically similar action to jumping on the trampoline as both the triple extension and subseuent triple extension of the lower limbs is evident during trampoline jumping. However, there are differences in the way the gymnast interracts with the rigid and compliant surfaces, respectively, and the subseuqent forces experienced. A trampoline jump is dictated largely by the elastic nature, and in the turn the contact time, of the bed. During the floor based CMJ the gymnast must perform both flexion and extension of the lower limbs whilst in contact with the ground. In contrast during a trampoline jump, the entire flexion phase occurs exclusively in the downward aerial phase prior to contact with the bed, with hip and knee angles on contact with the being reported between 25-40° and 20-40°, respectively (Qian et al., 2020; Rupf & Chapman, 2013). Gymnasts also begin to extend the lower limbs prior to contact with the bed as they fall from height, and continue through lower limb extension on contact with the trampoline bed, with both hip and knee angles reported to be less than 10° at the end of the jump cycle (Rupf & Chapman, 2013). Despite differences in how the gymnast's lower limb flexion and extension occurs on the trampoline with respect to the jumping surface itself compared to the CMJ, the biomechanical actions remain similar which may underpin the significance of the CMJ height variable with respect to ToF reported in this study.

There were differences in the relationship between reactive strength and ToF performances between senior and junior gymnasts. Specifically, 10 to 5 RSI explained 13% of the variance between total ToF in junior gymnasts, however there was no significant correlation with total ToF in senior gymnasts. The 10 to 5 RSI test is plyometric in nature with contact times of less than 250 ms exhibiting a fast SSC, which is considerably shorter than average contact time observed in the 20-max performance test (0.32 s). RSI is significantly greater in athletes post-peak height velocity compared to pre-peak height velocity athletes (Baker et al., 2022). In this study, 10 to 5 RSI was the only variable that significantly correlated with age ($r = 0.59$, $p < 0.05$) for the junior gymnasts, suggesting there could be a maturational element to the 10 to 5 RSI test, that is not evident across the other variables tested in this study. Conceptually, the contribution of 10 to 5 RSI to total ToF in junior gymnasts could be due to a maturation effect within the junior gymnasts, rather than indicating fast SSC plyometric ability is important for maximal trampoline performance, a posit supported by the lack of contribution to total ToF in the senior cohort.

There are limitations in this study that should be noted. It is suggested that at least 50 participants should be used when employing a multiple linear regression, compared to the 32 used in this study (Green, 1991). However, this study recruited all elite level gymnasts within the Great Britain high performance system and hence represents the entire population of a homogenous group. All testing was conducted during various national training camps, therefore gymnasts performed their normal training sessions between familiarisation and testing visits. Gymnasts use their arms as part of their technique when jumping maximally on the trampoline, however, none of the tests assessed the contribution of the upper body in maximal jumping performance. Finally, the measures derived from the load-velocity assessment (CMJ $F_0$, $V_0$ and $P_{MAX}$) are an extrapolation and estimation of values, and assumes gymnasts employ the same push-off distance during each CMJ as calculated prior to testing.

This study offers unique insight in to the relationship between a variety of floor based performance measures and maximal trampoline ToF in elite trampoline gymnasts. CMJ $F_0$ and CMJ height are both important predictors of maximal ToF, with CMJ $F_0$ of greater importance for senior gymnasts and CMJ height for junior gymnasts. Off-bed performance measures that in involve the triple extension of the lower limbs, exhibited greater relationships with maximal ToF, an action similarly observed on the trampoline. In particular the maximal strength of the lower limbs appears to be more important for maximal ToF, than reactive strength capabilities. The relationship observed between CMJ $F_0$ and maximal ToF could be attributed to the reported knee extension action observed on the trampoline, and the proposed underpinning determinants of CMJ $F_0$, such as the maximal isometric strength and size of the knee extensors. This information can be used to target specific, trainable physical qualities that can improve the determining factors observed in this study, and therefore have the potential to influence maximal ToF performance. For example, further research into the effects of training interventions to target maximal force capabilities of the lower limbs on ToF performance in warranted, to give additional insight in linking on and off bed performance.

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## Declaration of interest

No potential conflict of interest was reported by author(s).

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