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ORIGINAL RESEARCH

The relationship between handgrip strength and performance scores in North American Collegiate Division I women's artistic gymnasts

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Abstract. Maximal isometric handgrip strength (HGS) is used as an indicator of overall muscular strength and has also been found to be predictive of certain athletic events sporting prowess. Women's artistic gymnastics requires athletes have high levels of relative muscular strength and power to be successful. This study examined the relationship between HGS and gymnastics performance scores for the 4 events of vault, uneven bars, beam, and floor in female collegiate artistic gymnasts. Twenty-five (n=25) female National Collegiate Athletic Association (NCAA) Division I North American collegiate women's artistic gymnasts (age: 20.1±1.3 yrs; height: 158.9±5.6 cm; mass: 58.2±5.3 kg) were assessed for a one-time measurement of absolute HGS in kg and relative HGS (HGS/height in m^2), as well as their average vault, uneven bars, beam, and floor performance scores across a competitive season. Pearson correlation coefficients (r) were determined between HGS and all performance scores. No significant ($p > 0.05$) correlations were found between absolute HGS (30.8±4.4 kg) or relative HGS (12.0±1.6 kg/m^2) and any 4 gymnastics event's performance scores (r range: -0.07 – 0.50 or r range: -0.06 – 0.31, respectively). In this female collegiate gymnastics' population, 56% had an absolute HGS and 80% had a relative HGS, respectively, above the 50th percentile of all similarly aged adult females in the United States. In the current population of female collegiate gymnasts, absolute and relative HGS were not related to any gymnastics events performance scores and adds to the existing literature, supporting no relationships between HGS and sports performances where sports movements require a high degree of technical precision and accuracy. Findings from this investigation can be used by athletes, coaches, and practitioners in the collegiate women's gymnastics realm to assess if athletes have attained sufficient absolute HGS, and especially relative HGS values, to be successful.

Keywords: Absolute, dynamometer, gymnastics, normative, relative.

Introduction

The sport of gymnastics is separated into 6 different disciplines including rhythmic gymnastics, trampoline gymnastics, aerobic gymnastics, acrobatic gymnastics, and men's and women's artistic gymnastics (Bale & Goodway, 1990; Heiniger & Mercier, 2021). Due to the international coverage at world events like the world championships and the Olympics, artistic gymnastics are easily the most popular styles for participation worldwide (Bale & Goodway, 1990). Although the 5 other disciplines of gymnastics vary in terms of what is needed to be successful, the focus of the current investigation will be women's artistic gymnastics due to the paucity of literature in the collegiate population in general, including in the United States. Women's artistic gymnastics includes 4 pieces of apparatus events including the vault, the parallel uneven bars, the balance beam, and floor. At the international level, the International Gymnastics Federation (FIG) sets the standards for performance for each event via a code of judging (Code of Points) that is updated every 4 years

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(Bale & Goodway, 1990; Fink et al., 2015). The updated judging standards are used by national level gymnastics agencies, such as the United States of America Gymnastics governing body. Further, the judging in gymnastics is largely subjective based on qualitative aspects, like body image and technique execution, and is even influenced by nationality (Heiniger & Mercier, 2021) or university bias (Gymjudgerob, 2020; Minehart, 2019). But, there are important quantitative components for women's artistic gymnastics such as high levels of muscular strength, muscular power, coordination, and flexibility as well as maintaining a lean body type that allows the athletes to develop relative muscular strength and power (Bale & Goodway, 1990; French et al., 2004).

Handgrip strength (HGS) has a been used to predict overall upper- and lower-body muscular strength and muscular endurance (Cronin et al., 2017; Trosclair et al., 2011). Further, muscular strength is an important component of overall health (García-Hermoso et al., 2018), as well as sports performance (Suchomel et al., 2016); and both someone's health as measured by all-cause mortality risk (Gale et al., 2007; Sayer et al., 2006) as well as certain sports' performances (Cronin et al., 2017) can be predicted from measuring HGS. While health outcomes being predicted by HGS is important, the focus of this investigation will be on HGS and sports performance.

As comprehensively reviewed by Cronin et al. (2017), HGS is a unique component of sport performance that may be easily overlooked since not all sports utilize this task, but many sports require a sufficient, if not high degree, of HGS for maximizing performance potential and also reducing injuries (Cronin et al., 2017). Further Cronin et al. (2017) described the hand as a complex anatomical system that involves 27 bones and 15 joints and has ~30° of movement freedom (rotational and translation) and is designed to apply force and grasp objects/implements to perform precisely controlled movements. Cronin et al. (2017) broke down sport specific HGS needs into 4 categories including hand-to-projectiles, hand-to-implement, hand-to-immovable apparatus, and hand-to-hand combat, which comprises a variety of sports needing HGS. Further, the type of grip needed by sport can be categorized into a "power grip" needed to grasp cylindrical-shaped objects (e.g., bats, sticks, rackets, barbells) or "precision grip" needed to grasp sphere-shaped objects (e.g., balls) and most sports require a combination of both grip types (Cronin et al., 2017).

HGS has been found to be predictive of certain sports performance measures in many sports (readers are again referred to the Cronin et al. 2017 review), including but not limited to boxing (Guidetti et al., 2002), climbing (Wall et al., 2004), golf (Wells et al., 2009), mountain biking (Chidley et al., 2015), soccer (James et al., 2017), American collegiate football (Otterson & DeBeliso, 2020), and strength sports (Suazo & DeBeliso, 2021), to name a few. In general, HGS seems to be predictive during movement patterns with large forces and/or torques at high velocities, due the relationship with HGS and overall muscular strength and power (Cronin et al., 2017). In contrast, sport movements that require low forces and/or torques at low velocities and/or require a high degree of technical (e.g., movement coordination, sequencing, and timing) precision and accuracy are poorly predicted by measuring HGS (Cronin et al., 2017). Sports movements that are not predicted by measuring HGS include, but are not limited to, baseball batting average (Fry et al., 2011; Mangine et al., 2013), basketball points, assists, and blocks per game (McGill et al., 2012), bowling scores (Tan et al., 2001), cricket spin-off/bowling score (Amritashish & Shiny, 2015), ice hockey shot accuracy (Alexander et al., 1963), number of throws and attacks in a judo match (Franchini et al., 2005), racquetball success (Layton & DeBeliso, 2017), and field hockey slalom sprint and dribble tests (Sharma et al., 2012; Wassmer & Mookerjee, 2002), to name a few. HGS can also predict training experience/training and can help a practitioner delineate subelite from elite athletes as well as predict athlete's that will have successful performances versus those who will not be successful in their respective sports (Cronin et al., 2017). Therefore, HGS can be used as a convenient cost-effective objective muscular strength measurement in athletes to track progress, prevent injuries, as well as predict sports performance in certain sporting movements where HGS may be related.

The sport of gymnastics is currently lacking literature pertaining to HGS as a predictor of any direct sport performance event outcomes (Cronin et al., 2017). In the only study, to our knowledge, to examine HGS in relation to gymnastics performance in mature (~20 yrs) female gymnasts, Pool et al. (1969) found HGS to not be related to gymnastics performance rankings (i.e., from 1st to 42nd) competing at the 1967 European championships. However, the sport of women's artistic gymnastics has dramatically changed since 1967 (Bale & Goodway, 1990; Heiniger & Mercier,

2021) and this same study did not measure actual performance event scores, only rankings. In the only other study to examine HGS as a potential predictor in gymnastics, Ruprai et al. (2016) found that HGS was strongly related (*r* = 0.82) to HGS endurance in male artistic gymnasts. However, this study also did not measure any performance measures from male artistic gymnastics events directly (e.g., pommel horse, vault, floor, high bar, parallel bars, or rings scores were not reported). Therefore, research is still warranted to examine HGS as a predictor of gymnastic event performance outcomes in any style of gymnastics, including collegiate gymnastics. As the focus of this investigation is collegiate women's artistic gymnastics, of the 4 events they compete in the vault, the beam, and the floor events likely require too much technical precision and accuracy independent of the magnitude of handgrip forces and also these events generally, with exceptions, use lower forces, torques, and velocities during many event movements to have the performance scores predicted by measuring HGS. Conversely, HGS is anecdotally thought to be an integral component for success in the uneven bars (Cronin et al., 2017) and therefore deserves experimental evidence and may be predictive of uneven bars success. Therefore, the purpose of this study was to determine the relationship between isometric muscular handgrip strength (HGS) and gymnastics performance scores in National Collegiate Athletic Association (NCAA) Division I North American collegiate female gymnasts. We hypothesized that HGS will have a relationship with the uneven bars performance scores, but there will be no relationship between HGS and the vault, the beam, or the floor performance scores. Findings from this study will help to elucidate the role HGS has on predicting women's artistic gymnastics performance event scores. Further, this study will provide the first evidence of absolute and relative HGS values in collegiate Division I women's artistic gymnasts.

Methods

Participants

The sample used in this study was twenty-five (n=25) female NCAA Division I collegiate women's artistic gymnasts in the United States with their characteristics displayed in Table 1. Subject recruitment was done by word-of-mouth. Since the sample was gathered from college gymnastics, there were no participants under the age of 18 years old. Prior to participation in this study, all subjects read and voluntarily signed an informed consent. This study was approved by Southern Utah University's Institutional Review Board (#23-022022c) prior to commencement. The research was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Instruments and Apparatus

Each participant's HGS was tested with the hydraulic Jamar hand dynamometer using their dominant hand while seated to measure each individual's maximal isometric handgrip strength. The Jamar hand dynamometer has been described as the gold-standard device for maximal isometric handgrip strength measurements (Cronin et al., 2017; Roberts et al., 2011). Bellace et al. (2000) found the Jamar hand dynamometer to be a highly valid (ICC = 0.99) and reliable (ICC = 0.98) measurement of handgrip strength in healthy adults 20-50 years old. Further, the Jamar hand dynamometer has the most extensive normative reference data to compare to (Roberts et al., 2011). This study also used a computer with internet access to obtain the gymnastics scores through the University's gymnastics websites for the 4 women's artistic gymnastics performance events – the vault, the uneven bars, the beam, and the floor.

Procedures

Absolute and relative maximal isometric handgrip strength (HGS)

Participants in this study had their maximal isometric handgrip strength (absolute HGS) measured in a single session following previously published protocols (Suazo & DeBeliso, 2021). Participants HGS was measured with the hydraulic Jamar hand dynamometer. The HGS measurement had all subjects use a standard position. Including, a consistent hand position (second position), wrist position (0-30 degrees of dorsiflexion), forearm position (neutral), shoulder position (adducted, naturally rotated), elbow position (90 degrees of flexion), posture (seated), time intervals, and one hand (dominant) (Suazo & DeBeliso, 2021). Once in standard position, the participant was instructed to, "squeeze as hard as possible while maintaining standard position." There were three trials completed, with 1-minute rest in between. The HGS for each trial was recorded and the average of the top two trial scores was used as the maximal HGS (absolute HGS) value for each participant (Suazo & DeBeliso, 2021).

To account for differences in body size, relative HGS was determined based on a recent publication (Nevill et al., 2021) establishing height^2 as the single best body size metric to normalize HGS to (i.e., HGS in kg/height^2 in meters). Absolute HGS for each participant was compared to normative reference values established from 1232 adults from 18-85 years old in the US (Wang et al., 2018). Relative HGS for each participant was compared to normative reference values established from 8690 adult from 20 years and older in the US (Nevill et al., 2021).

Gymnastics performance scores

The gymnastics performance scores were accessed through the University's gymnastics website. Here, the results of each participant's average score across a competitive season on each woman's gymnastics event (vault, uneven bars, beam, and floor) were collected for the events the participants competed in. Some participants only competed in one event, some participated in several or all events, and some participants competed in no events. Only participants who competed in one or more of the four events were used for HGS and performance scores analyses. Women's artistic gymnastics events scores are determined by the individual athlete's routine which is evaluated by a panel of judges on the routine's difficulty, artistry, and execution components (Heiniger & Mercier, 2021). Judges in the panel grade the performance with a mark of 0 to 10 at increments of 0.1 for each of the routine's components. The performance is based on the judge's deductions for a precisely defined perfect 10 score for each of the 4 event's apparatuses from the FIG's Code of Points (Heiniger & Mercier, 2021), which is followed at the collegiate level in the United States. The composition and number of judges on a panel varies by gymnastic disciplines as well as competition level, but the final performance scores is made up of the aggregate marks given for each judge on the panel (Heiniger & Mercier, 2021).

Figure 1. Some woman's artistic gymnastics events would appear to rely heavily upon handgrip strength for successful performance (image courtesy of Southern Utah University Athletics).

Design and Analysis

This study gathered variables for analysis including age, height (centimeters), mass (kg), absolute HGS (kg), relative HGS (HGS/height^2), and their 4 event (vault, uneven bars, beam, and floor) gymnastics' performance scores. Descriptive statistics were calculated for all of the above variables and data are presented in mean ± SD. A Pearson correlational analysis was used to compare absolute HGS and relative HGS to gymnastics performance scores. Pearson correlational analyses were also used to examine absolute HGS and relative HGS to age. Pearson correlation coefficient (r value) was generated for every comparison. The strength of the relationships was based on the correlation coefficient as follows: very strong 0.8-1.0, strong 0.6-0.79, moderate 0.4-0.59, weak 0.2-0.39, and very weak 0-0.19 (Liang et al., 2019). Statistical significance was set a priori at $p < 0.05$. GraphPad Prism 9 was used for all analyses.

Results

Twenty-five female collegiate artistic gymnasts participated in the study, with their characteristics listed in Table 1. Participant's average scores of the 4 gymnastics events are found in Table 2, with not all participants (n=7-12) participating in every event. The participant's three trials and average absolute HGS as well as average relative HGS are found in Table 3. The Pearson correlation coefficient's (r value) between absolute/relative HGS and the 4 women's artistic gymnastics events (vault, uneven bars, beam, floor) performance scores are presented in Table 4. Absolute HGS (r = -0.08, p = 0.71) and relative HGS (r = -0.21, p = 0.31) displayed a very weak and weak relationship, respectively, to the participants age. The participant's absolute HGS and relative HGS are compared with normative data in Table 5.

Table 1
NCAA division I collegiate woman artistic gymnasts characteristics.*

	Age (years)	Height (cm)	Mass (kg)
Female (n=25)	20.1 ± 1.3	159.9 ± 5.6	58.2 ± 5.3

**Data are in mean±SD. NCAA = National Collegiate Athletic Association, cm = centimeters, kg = kilograms.*

Table 2
Gymnastics competition event average scores.*

	Vault (n=11)	Uneven Bars (n=7)	Beam (n=10)	Floor (n=12)
Female (n=25)	9.72 ± 0.09	9.75 ± 0.05	9.58 ± 0.19	9.47 ± 0.43

**Data are in mean ± SD.*

Table 3
Gymnastic athlete's absolute and relative HGS information.*

	Absolute HGS Trial 1	Absolute HGS Trial 2	Absolute HGS Trial 3	Absolute HGS (Highest Two Trials Mean, kg)	Relative HGS (Absolute HGS in kg/height in m^2)
Female (n=25)	30.3 ± 5.0	30.1 ± 4.4	29.7 ± 4.3	30.8 ± 4.4	12.0 ± 1.6

**Data are in mean ± SD. HGS = handgrip strength, kg = kilograms, m = meters.*

Table 4
Relationship between competition event average scores and absolute or relative HGS.*

Event	Absolute HGS *r*	*p*	Correlation Strength	Relative HGS *r*	*p*	Correlation Strength
Vault	0.50	0.12	Moderate	0.31	0.36	Weak
Uneven Bars	-0.36	0.42	Weak	-0.24	0.60	Weak
Beam	-0.07	0.84	Very weak	-0.06	0.86	Very weak
Floor	0.13	0.69	Very weak	0.10	0.76	Very weak

**Data are in mean±SD. HGS = handgrip strength, r = Pearson correlation coefficient.*

Table 5
Gymnastic athlete's measured absolute and relative HGS compared to normative values.[*]

Participant	Age (yrs)	Height (m)	Absolute HGS (kg)	Normative[¥] Percentile Range	Relative HGS (kg/m^2)	Normative[#] Percentile Range
1	21	1.63	36.0	75-<90	13.6	90-<95
2	21	1.58	33.0	50-<75	13.3	90-<95
3	20	1.60	36.0	75-<90	14.1	95-<97
4	22	1.65	27.0	25-<50	9.9	20-<30
5	21	1.68	35.0	75-<90	12.5	80-<90
6	19	1.52	31.0	50-<75	13.4	90-<95
7	20	1.58	27.5	25-<50	11.1	50-<60
8	18	1.65	35.0	75-<90	12.8	80-<90
9	22	1.58	26.5	25-<50	10.7	30-<50
10	20	1.68	27.0	25-<50	9.6	20-<30
11	21	1.68	30.0	50-<75	10.7	30-<50
12	19	1.47	26.5	25-<50	12.2	80-<90
13	21	1.58	38.0	75-<90	15.3	>99
14	23	1.63	29.5	50-<75	11.2	50-<60
15	20	1.65	31.5	50-<75	11.6	60-<70
16	18	1.55	27.0	25-<50	11.3	60-<70
17	19	1.52	26.0	25-<50	11.2	50-<60
18	19	1.65	37.5	75-<90	13.8	95-<97
19	19	1.60	32.0	50-<75	12.5	80-<90
20	21	1.58	27.5	25-<50	11.1	50-<60
21	19	1.58	27.5	25-<50	11.1	50-<60
22	19	1.68	36.5	75-<90	13.0	80-<90
23	19	1.52	26.5	25-<50	11.4	60-<70
24	20	1.60	37.0	75-<90	14.5	97-<99
25	21	1.58	23.5	25-<50	9.5	10-<20

**Data are in mean±SD. HGS = handgrip strength, m = meters, kg = kilograms. [¥]Normative reference percentiles for age and sex for absolute HGS were obtained from Table 1 (Wang et al., 2018). [#]Normative reference percentiles for age and sex for relative HGS were obtained from Table 4 (Nevill et al., 2021). For instance, Participant 1's absolute HGS measures between the 75th and 90th percentile of all 18-24 year old women and relative HGS measures between the 90th and 95th percentile of all 20 year old women in the United States.*

Discussion

The purpose of this study was to determine if there was a relationship between absolute/relative HGS and gymnastics performance scores across the 4 events of vault, uneven bars, beam, and floor in North American NCAA Division I collegiate women's artistic gymnasts. It was hypothesized that there would only be a positive linear relationship between HGS and uneven bar scores. Our results only supported part of this hypothesis as there was no significant relationships between absolute/relative HGS and any of the 4 performance events average scores in this sample of collegiate women's artistic gymnasts. Another novel aspect of this study is that we report the individual and average absolute (in kg) and relative HGS (kg/m^2) in a sample of North American competitive collegiate female artistic gymnastics for the first time. In this female collegiate gymnastics' sample, 56% of athletes had an absolute HGS and 80% of athletes had a relative HGS, respectively, above the 50^{th} percentile (i.e., population average) of all similarly aged healthy adult females in the United States. Findings from this investigation can be used by athletes, coaches, and practitioners in the collegiate women's gymnastics setting to assess if athletes have attained sufficient absolute HGS, and especially relative HGS values to be competitive.

There are several reasons for the potential lack of significant relationships between HGS and collegiate women's artistic gymnastics performances scores observed in the current investigation. These include, 1) the single measurement of the magnitude of HGS does not predict the coordination, sequencing, and timing of the forces needed for the hand movement; 2) performance scores can be easily influenced by the biased judging in gymnastics as well as the qualitative aspects of the events needed for success; and 3) although a sufficient HGS is required, many of the sport of gymnastics' sports-specific movements require high technical precision and accuracy which are not typically related to HGS in other sports (Cronin et al., 2017). In regards to the first reason, it has been argued that that the coordination, timing, and sequencing of the hand's forces and pressures to an object/implement are more important than the magnitude of the HGS applied (Cronin et al., 2017). Further, a single measurement of the magnitude of HGS does not measure the coordination, timing, and sequencing of the hand or any other body parts movement, and therefore this is likely the reason in sports where sport-specific movement success is predicated on technical precision and accuracy, HGS is a not a good predictor of sports performance (Amritashish & Shiny, 2015; Cronin et al., 2017; Franchini et al., 2005; Fry et al., 2011; Mangine et al., 2013; McGill et al., 2012; Sharma et al., 2012; Layton & DeBeliso, 2017; Tan et al., 2001; Wassmer & Mookerjee, 2002). Indeed, in the current investigation, the 4 events in collegiate women's gymnastics are predicated on high levels of technical precision and accuracy for success and therefore a measurement of the magnitude of HGS was not enough to predict performance outcomes. Our research hypothesis did predict that the vault, the beam, and the floor routines performance scores would not be related to HGS. However, due to the anecdotal belief that HGS is important for uneven bars success (Cronin et al., 2017), we predicted that HGS would be related to the uneven bars event, and it was not. The lack of relationship between HGS and uneven bar performance scores is likely, again, due to the technical precision and accuracy needed in the uneven bar's movements, beyond just the magnitude of HGS applied. While a sufficient HGS alone is needed relative to similar level women's gymnastics athlete for success in the sport (discussed below), none of the 4 events in North American collegiate women's artistic gymnastics are predicted by the magnitude of HGS alone.

The second reason for lack of relationships between HGS and gymnastics performance scores could be due to the influence subjective qualitative characteristics in judging (e.g., body image or technique execution) or university/leotard judging biases could have on performance scores. Indeed, judges have been found to bias towards certain body images in women's collegiate gymnastics performance scores (Falls & Dennis Humphrey, 1978; Valiquette, 1996), although this was not assessed in the current investigation. Further, Heininger & Mercer found there to be national bias between traditional well performing gymnastic countries and countries not consistently winning in international level gymnastics (Heiniger & Mercier, 2021). This finding lends support to the anecdotal belief in the leotard or university bias from judges at the collegiate level in the United States (Gymjudgerob, 2020; Minehart, 2019). For instance, in the United States a lower score may be awarded for a gymnast from a less gymnastically renowned university compared to a gymnast from a more gymnastically renowned university, even when the two gymnasts performed the same routine (Gymjudgerob, 2020; Minehart, 2019). Therefore, in the current investigation on a sample of collegiate female gymnasts from a less gymnastically renowned university, the performance scores could easily have been biased and confound the results. Nevertheless, in the parameters of this study, no relationships were observed between HGS and the 4 performance events in women collegiate gymnasts.

The last potential reason for the lack of relationship between HGS and performance scores in the current investigation is that the gymnasts had sufficient HGS for their sport and thus no competitive advantage was to be gained from the individual athlete's variances in HGS (Cronin et al., 2017). In fact, Cronin et al. discussed across the studies the authors reviewed on HGS and sports performance, that once a threshold of sufficient HGS is attained by athletes that a performance advantage may not be obtained in sport movements where timing and/or scoring of technically precise skilled maneuvers is part of the performance score/strategy (Cronin et al., 2017). The current investigations women's gymnasts absolute HGS of 30.8 kg is considered sufficient according to a reported minimal HGS cut off value of 30 kg from the FIG's women's artistic gymnastics age group development program, which is used as a talent identification program internationally (Nassib et al., 2020). Further, to our knowledge, in the only other study of mature ~20-year-old female gymnasts to measure HGS and performance, Pool et al. reported an average HGS of 45±5.0 kg in the top 42 performers at the 1967 European championships. Interestingly, the same authors also found HGS to not relate to gymnastics performance placing (Pool et al., 1969). However, differences in hand dynamometer (Jamar versus Bettendorff dynamometer), competitive level (European championships vs NCAA collegiate Division I), and year of measurement (1967 versus 2022) make direct comparisons between the current investigation and the Pool et al. study difficult. Collectively, the current investigations female collegiate gymnasts appear to have already had sufficient HGS and this could account, in part, for the lack of relationship observed between HGS and gymnastic performance scores.

Another novel aspect of this investigation is that we report the individual and average absolute and relative HGS of North American Division I NCAA collegiate woman's artistic gymnasts for the first time (Table 5). In the current investigation, more than half of the participants (56%) had a dominant absolute HGS value above the 50^{th} percentile, with 32% being above the 75^{th} percentile of all 18-24 year old women in the United States (Wang et al., 2018). Likewise, the normative values for relative HGS show 80% of the participants were greater than the 50^{th} percentile of adult healthy female adults in the United States. Also, 52% of participants were above the 80^{th} percentile, 28% were above the 90^{th} percentile, and one athlete was above the 99^{th} percentile (15.3 kg/m^2) of all reported 20 year old women in the United States (Nevill et al., 2021). This data indicates that while sufficient absolute HGS (i.e., 30.8 kg on average) is important in collegiate women's artistic gymnasts, relative HGS and thus relative muscular strength, is more important. Investigators often normalize HGS to some measure of body size for a more sensitive indicator of strength within a population, and Nevill et al. (2021) again recently identified height in meter^2 to be the single best body size dimension to normalize HGS to in 8690 adults in the United States. To our knowledge, the normalized relative HGS values (in height in m^2) are the first to be reported on any female athlete population and therefore there are no studies to compare to. However, there are numerous studies to compare the current investigations female collegiate gymnasts absolute HGS values to (Cronin et al., 2017; Haynes & DeBeliso, 2019; Ruggieri & Costa, 2019; Suazo & DeBeliso, 2021). Indeed, Kaplan et al. reported comparable dominant absolute HGS values to the current investigation in elite Turkey female athletes (~20 yrs old), including basketball (32.00±0.04 kg), volleyball (29.95±3.27 kg), badminton (31.57±3.38 kg), and handball (33.51±3.68 kg). Similarly, the current investigations dominant absolute HGS was comparable to strength athletes with strong (relative to their body mass) upper-body strength (0.9 bench press 1RM/BM, 1RM to body mass ratio) and lower-body strength (1.5 RM/BM squat, 1.8 RM/BM deadlift) measures (Suazo & DeBeliso, 2021). Specifically, in 30 female powerlifters (28.9±5.5 yrs) in the United States, dominant HGS was 32.0±7.1 kg (Suazo & DeBeliso, 2021), which is comparable to the current female collegiate gymnasts absolute HGS. In addition, 15 female CrossFit athletes (30.9±7.1 yrs) had a dominant HGS of 29.7±4.9 kg (Haynes & DeBeliso, 2019). In comparison, the current female gymnasts had an ~17% higher dominant absolute HGS compared to 13 recreational female aerialists (32.8±6.3 yrs) in the United States (Ruggieri & Costa, 2019). Taken together, these results suggest that a sufficient absolute HGS is required for competitive events involving muscular strength. Further, relative strength appears to be more important than absolute strength in competitive female collegiate gymnasts.

There are a few limitations to this study. The first limitation is the sample of collegiate gymnasts was from one NCAA collegiate Division I university in the United States and was relatively small (n=25). Inclusion of different universities across the United

States, particularly in the context of university/leotard bias (Gymjudgerob, 2020; Minehart, 2019), could provide differing results and is thus warranted. Nevertheless, this study provides the first evidence of absolute and relative HGS values, as well as absolute/relative HGS values relationships to the 4 gymnastic performance events in collegiate women's artistic gymnastics. The second limitation is that not all athletes competed in all 4 gymnastic events. Due to the desire for a team to be competitive at the collegiate level, often times individual gymnasts only perform the events they are the most competitive in. However, this is a common practice in collegiate gymnastics and therefore our results are from a real-world, competitive, collegiate setting and are thus, meaningful. The final limitation is the HGS measurement used. Specifically, an alternate measurement of HGS may be more insightful than the single measurement of the magnitude of HGS used herein. Understanding other hand measurements like pinch grip strength, hand size, hand length, or even timing, coordination, and sequencing of hand forces within competitive events through alternative measurements like the GripForce Map system (DeBeliso et al., 2013) may provide more specific insight into hand use in sport-specific movements, including gymnastics (Cronin et al., 2017).

In conclusion, this study found that there is no meaningful relationship between absolute/relative HGS and the 4 gymnastic performance event scores in a sample of North American NCAA Division I collegiate women's artistic gymnasts. These findings are corroborated by other studies that have found no relationship between HGS and sports performance in sport movements that require high levels of technical precision and accuracy (Cronin et al., 2017), similar to the 4 events studied herein. Moreover, more than half (56%) and 80% of the current sample of female collegiate gymnasts had an absolute HGS and relative HGS, respectively, above the 50th percentile of all similarly aged healthy female adults in the United States. These findings suggest that relative muscular strength appears to be more important than absolute HGS in female collegiate gymnasts, even though a sufficient HGS is needed for all gymnasts to be successful. The results from this study can be used by athletes, coaches, and practitioners in the collegiate women's gymnastics realm to help identify and track athletes so that they can obtain sufficient absolute HGS, and potentially more importantly relative HGS, to be competitive gymnasts.

Authors' Contribution

Study Design: HN, MD, MML; Data Collection: HN, MD; Statistical Analysis: MD; Manuscript Preparation: HN, MML; Funds Collection: MML.

Ethical approval

This study was approved by Southern Utah University's Institutional Review Board (#23-022022c) prior to commencement. The research was conducted in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

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Conflict of Interest

No funding was received for this research. There are no conflicts of interest with the authors related to this research.

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