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A Brief Review of Handgrip Strength and Sport Performance

Authors: John Cronin[1,5], Trent Lawton[1,3], Nigel Harris[1,2], Andrew Kilding[1], Daniel Travis McMaster[4]

[1]Sports Performance Research Institute New Zealand
AUT University
Private Bay 92006
Auckland 1020, New Zealand

[2]Human Potential Centre
AUT University
Private Bay 92006
Auckland 1020, New Zealand

[3]High Performance Sport New Zealand
Gallagher High Performance Centre
Cambridge 3494, New Zealand

[4]Health, Sport and Human Performance
University of Waikato
Tauranga 3116, New Zealand

[5]School of Medical and Health Sciences
Edith Cowan University
Perth, Australia

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Corresponding Author:
Daniel Travis McMaster
Health, Sport and Human Performance
University of Waikato
Tauranga 3116, New Zealand
New Zealand
+647 838 4466 Ext. 9476
dmcmaste@waikato.ac.nz

ABSTRACT

Tests of handgrip strength (HGS) and handgrip force (HGF) are commonly used across a number of sporting populations. Measures of HGS and HGF have also been utilized by practitioners and researchers to evaluate links with sports performance. This article, firstly evaluates the validity and reliability of various handgrip dynamometers (HGD) and HGF sensors, providing recommendations for procedures to ensure precise and reliable data are collected as part of an athlete testing battery. Secondly, the differences in HGS between elite and sub-elite athletes and the relationships between HGS, HGF, and sports performance are discussed.

KEY WORDS: Grip strength, grip force, reliability, validity, sport performance, athletes

INTRODUCTION

Strength and conditioning coaches are interested in measures that can objectively monitor progress and guide programming for rehabilitation and strength training of the hand, forearm and surrounding musculature. The hand is a complex anatomical system comprised of 27 bones and 15 joints with approximately 30 degrees of rotational and translational freedom designed to grasp and apply force to objects of all shapes and sizes, and perform a combination of intricate finely controlled movements (118). A number of sports where grasping and force application is important, such as baseball, climbing, golf, hockey, paddling, swimming, tennis, weightlifting and wrestling, require a sufficient, if not high degree of handgrip strength (HGS) for optimizing performance and potentially preventing injury. Practically, such measures would need to be affordable, portable, reliable and sensitive to detecting meaningful change in performance. The challenge for practitioners is to find measures that fulfil the aforementioned criteria and utilize them to guide training to a better effect. One measure that may fulfil such criteria could be the use of handgrip dynamometry (HGD) to measure maximum isometric HGS.

A number of HGD review articles have been published addressing the reliability, validity and standardization of HGS testing protocols across a range of populations (79, 82, 141, 186); however, only one brief review to date has addressed the effectiveness of HGS testing in athletes (186). From a sports performance perspective it is of interest to learn how HGS relates to and effects sports specific actions and movements patterns. This review aims to, firstly provide insight into the validity and reliability of HGS and handgrip force (HGF) assessment protocols, which would aid practitioners in selecting the appropriate method and device for testing; and secondly to examine the relationships between HGS and sport performance to determine if increased HGS contributes to improved sports performance.

Literature Search

The following electronic data bases were searched: MEDLINE, EBSCO Host, Google Scholar, IngentaConnect, Ovid LWW, ProQuest Central, PubMed Central, ScienceDirect Journals, SPORTDiscus and Wiley InterScience. The following keywords were used in various combinations during the electronic searches: hand, grip, dynamometer, dynamometry, strength, force, maximum, effort, isometric, static, measure, output, quantify, assess, evaluate, test, reliability, validity, sport, athlete, performance, physical, physiological, biomechanical, profile, correlation, relationship, comparison, difference, elite, novice, amatuer, and sub-elite. The searches identified 11,400 potentially relevant articles. Following a review of titles and abstracts, the total was reduced to 203. Original research articles, technical notes, and conference abstracts written in English focusing on HGD, HGS, and HGFs in all healthy human population groups (e.g. athletes, general population, adolescents, teenagers, adults, and elderly) were included in the initial screening phase. Final selections were based on the following inclusion criteria; a) studies that reported on the reliability and validity of HGD and HGS testing protocols across all healthy human population groups (N = 39), b) studies that reported the differences in HGS between elite and sub-elite athletes (N = 31), and c) studies that investigated the relationships between HGS and sport performance (N = 74). The number of articles included in this review focusing on HGS, handgrip force (HGF), and sports performance are as follows: baseball (n = 18), basketball (n = 2), bowling (n = 2), boxing (n = 1), climbing (n = 8), canoe (n = 1), cricket (n = 3), equestrian (n = 2), field hockey (n = 3), American football (n = 3), European football (n = 1), golf (n = 8), gymnastics (n = 1), handball (n = 3), ice hockey (n = 3), judo (n = 5), lacrosse (n = 1), mountain biking (n = 1), powerlifting (n = 1), rowing (n = 1), rugby (n = 1), swimming (n = 5), tennis (n = 9), volleyball (n = 3), waterpolo (n = 5), weightlifting (n = 1), and wrestling (n = 6).

Data Analysis and Interpretation

Interclass correlation coefficients (ICC) were reported to assess the inter-trial and inter-day reliability of a given HGD and HGS testing protocol. Pearson product moment correlations (*r*) were reported to determine the association between HGS and sport performance. The following correlation thresholds were used to determine the reliability of the respective HGS testing protocols (ICC) and relationships to sport performance (*r*): *trivial* (≤ 0.10), *small* (0.10-0.30), *moderate* (0.30-0.50), *large* (0.50-0.70), *very large* (0.70-0.90), and *nearly perfect* (≥ 0.90) (77). Cohen's effect size calculations ($ES = [X_{elite} - X_{sub\text{-}elite}] / SD_{sub\text{-}elite}$) and *p-values* (< 0.05) were also used to assess the differences in HGS between elite and sub-elite athletes. *ES* differences were interpreted as *trivial* (< 0.10), *small* (0.10 – 0.30), *moderate* (0.31 – 0.60), *large* (0.60 – 1.20), and *very large* (> 1.20) (150).

PART 1. VALIDITY AND RELIABILITY OF HANDGRIP STRENGTH DYNAMOMETERS AND TESTING PROTOCOLS

Validity of handgrip strength dynamometers

Given the various commercially available manufacturing designs and mechanisms to measure HGS (e.g. hydraulic, spring, strain gauge and pneumatic), practitioners may be concerned whether the accuracy and validity of HGD's is an adequate estimate of 'true' isometric HGS. Sealed hydraulic dynamometers measure grip force (kgf). The pneumatic systems measure grip pressure (mmHg, PSI [lbs/in^2], or Pascals) via the compression of air-filled compartments. Mechanical systems detect the amount of spring tension (kgf). The strain gauge systems detect changes in electrical resistance due to strain and force (Newton's) applied to the system. Electronic systems often incorporate a hydraulic dynamometer and a strain gauge to improve the accuracy of the force measurement.

Calibration studies conducted by Bellace et al. (11) and Cadenas-Sanchez el al. (21) found measurement errors of less than 1, 2, and 4% for the Jamar hydraulic, Dexter strain gauge, and TKK dynamometers, respectively. However, Shectman et al. (158) found measurement errors of 1.6 and 7.5% for DynEx and Jamar hydraulic dynamometers, respectively. They also observed force differences of 4 to 10% between the Jamar and DynEx dynamometers across a range of known loads (9.1 to 45.4 kg). Dynamometer inter-changeability has been evaluated mainly by comparing the Jamar hydraulic dynamometer as the apparent 'gold standard' with newer yet to be validated dynamometers. Guerra and Amaral (65) determined that when four different devices (hydraulic, spring loaded, and pneumatic) were compared to a known laboratory standard (Jamar hydraulic dynamometer), the correlations between the criterion force (hydraulic dynamometer) and that measured by each device was found to be *nearly perfect* ($r > 0.96$). These findings are in agreement to previous research, where *nearly perfect* correlations ($r \geq 0.90$) were also observed between hydraulic and strain gauge dynamometers

(10, 111). In contrast, *moderate* to *nearly perfect* correlations (r = 0.41-0.98) were observed between hydraulic dynamometers and various pneumatic dynamometers (44, 70, 105, 167). A more recent study, found the Wii balance board to provide valid (r = 0.80-0.88) measures of HGS in comparison to a previously validated hydraulic dynamometer (13).

It is recommended that HGD's not be used interchangeably to measure and monitor HGS changes over-time (79, 140). Given interchangeability is not recommended, practitioners should purchase devices that remain durable for the period of any investigation required. In terms of durability, it appears that dynamometers manufactured using strain gauges may be preferable to spring-based or hydraulic pressure systems, as the latter may produce erroneous data due to wear and tear of metal, slow leaks, or hysteresis (154). This emphasizes the importance for practitioners to maintain calibration standards, with some authors recommending dynamometer calibration every 4 to 6 months to ensure longitudinal validity is maintained (154).

A standardized testing position is particularly important when assessing HGS given the multi-articular functions of the hand and forearm muscles (79). Without standardization, variations in HGS may simply be related to changes in assessment protocols. The American Society of Hand Therapists recommends participants in a clinical setting are assessed sitting in a straight-back chair, with feet flat on the floor, shoulders adducted and neutrally rotated, elbow flexed at 90°, forearm in neutral position with the wrist self-selected between 0-30° extension and between 0-15° ulnar deviation (43). However, other studies:

- Found that standing produced *moderately* larger HGS outcomes in comparison to sitting (ES = 0.81); sitting produced *trivial* to *moderately* different HGS outcomes in comparison to laying supine (ES = -0.11 to 0.52); and laying (supine and prone) had a *very large* negative effect (*ES* = 1.59 and 2.17) on HGS in comparison to standing (37, 139). These findings indicated the importance of standardizing body position and posture during HGS assessment.

- Recommend a fully extended elbow as it allows a greater HGS measure than when compared to assessments taken with the elbow flexed at 90° (10, 38, 127, 171);
- Concluded that wrist position affected HGS measurement with forearm pronation and wrist flexion producing lower values than when compared respectively to neutral or extended positions (140). It appears the optimum wrist position may be self-selected (generally 35° wrist extension and 7° ulnar deviation) from which any deviation appears to decrease HGS.
- Found HGS was greatest with 180° of shoulder flexion (i.e. arm overhead) together with an extended elbow (171).

The reader should be cognizant that the aforementioned standardized clinical HGS testing protocols may not be appropriate and/or specific to the HGS positions and HGF requirements of sporting populations, which are subsequently addressed.

Reliability of handgrip strength testing

Once the essential body postures are clearly documented as a protocol, practitioners should ascertain other possible confounding factors warranting control or recording in notes, to stabilize interpretation of test-retest measures.

Inter-rater reliability is important when different assessors are involved in the measurement of individuals using the same device. Several studies have evaluated different assessors using identical HGS protocols, and reported *very large* to *nearly perfect* inter-rater reliability (ICC = 0.86 - 0.99 (94, 98, 126, 154). Inter-rater reliability was improved when two assessors were compared using the average of three measurements adhering to the same testing protocol. However, extensive protocol training or experience may not be required as inter-rater reliability did not differ notably over three consecutive trials for assessors with over 20 hours or less than 5 hours of testing experience (154).

HGS test-retest reliability time-points have ranged from three hours to 12 weeks depending on the testing protocol and population of interest. Large variability in the test-retest reliability findings (ICC = 0.48 to 0.99) have been reported in the literature (9, 13, 23, 38, 39, 46, 59, 60, 65, 69, 84, 93, 98, 110, 112, 119, 124, 127, 140, 158, 166, 188, 190). Given such broad ranges, it is recommended that practitioners quantify the reliability of their own assessment protocols, to gain insight as to whether procedures warrant review, or if the equipment is in need of replacing. The factors that warrant consideration when establishing a HGS protocol are summarized herewith (see Table 1):

- As it may be the case that practitioners will be monitoring small samples sizes ($n \leq 25$), a key recommendation was that at least three trials are recorded to provide better measurement reliability, irrespective of whether the maximum or mean score is examined (140). In general, the average of three measurements has proved more reliable (ICC = 0.93 - 0.99) than any single measurement (ICC = 0.86 - 0.97) (140).
- It is important to standardize and provide adequate recovery between trials (1-2 min) to minimize the effects of fatigue on HGS and maintain a high level of inter-trial reliability. Studies have reported that HGS declines with reduced inter-trial rest (15 – 60 s) due to a lack of recovery (increase in fatigue), which could be eliminated by increasing the duration of inter-trial rest (≥ 1 min) (66, 181). Subsequently, researchers that have adequate and clearly defined rest interval durations, reported *nearly perfect* inter-trial reliability (ICC = 0.92 – 0.99) (66, 145, 181). In contrast,

Dunwoody et al (34) implemented inter-trial rest periods of 2 min, and found that HGS increased (ES = 2.78; *very large*) from trial 1 to trial 4 in healthy college students, indicating a learning effect and possibly a post-activation potentiation effect. The effect post-activation potentiation protocols and inter-trial rest on HGS requires further investigation.

- It is important to standardize body and limb (segment) position across testing sessions to ensure high test-retest reliability. As discussed previously, using a seated vs. standing position, an extended vs. flexed elbow, and/or a supinated vs. pronated forearm positioning will inevitably influence HGS (37, 124, 125, 139, 140).
- The age and gender of participants appears to influence reliability as well as absolute HGS. When reassessed one week apart, HGS reliability in healthy ‘young to middle-aged’ adults was very strong (ICC = 0.99), although slightly lower test-retest values (*r* = 0.70) have been observed in young adults aged 18-25 years (71). Similarly, very low reliability (ICC = 0.48) was reported for adolescent girls (age = 13-17 yrs), in contrast their male (age = 13-17 yrs) counter-parts produced reliability (ICC = 0.98) (23). Werle et al. (194), found a curvilinear relationship between HGS and age in a large study (n = 1023) of 18 to 96 year olds, with HGS peaking in the 25 to 39 age group and declining gradually thereafter. Therefore, it is recommended that the age and gender of the sample be reported along with reliability for any established normative data.
- Similarly, it appears that occupation, leisure activity, sport, and training status may also affect HGS (97, 151). Josty et al. (83), for instance, reported that male office workers had significantly weaker HGS compared to equally aged car mechanics and farmers. Based on job demands, the magnitude of force required during repetitive HG tasks performed by a car mechanic and other physical occupations (e.g. grasping and

lifting heavy objects, using hand-tools, such as wrenches, ratchets, saws, drills, and hammers) will differ greatly in comparison to office workers (e.g. typing, clicking a mouse, filing, and answering the phone). Schick et al. (151), also reported significantly greater HGS in boxers comparison to mixed-martial artists. Practitioners should therefore take note of the physical demands of client's or subject's occupation and sport when comparing between subject HGS as part of monitoring or intervention evaluations.

- Studies have also reported that jaw clenching, wearing a mouth guard and consuming caffeinated energy drinks significantly increases HGS (20, 54); similar HGS increases were also observed when verbal encouragement was provided (39, 130).
- The effect of hand dominance on HGS assessment is not straightforward; however, based on population demographic studies, most samples will be comprised of 80-90% right-hand and 10-20% left-hand dominant individuals, respectively (81, 100). Regardless of hand dominance, researchers have found the dominant hand to be stronger, ranging from 0.1 to 16.5% (23, 61, 84). Nonetheless, if data is required to establish normative data for specific populations, it is recommended that practitioners note any right- and left- hand dominance in collection and subsequent analysis of data (140). It is unclear if hand dominance affects reliability; therefore we advise caution should practitioners wish to average the combined left- and right- hand measures. It is advised that data collected from both the dominant and non-dominant hands be presented to better inform the athlete and coaches of any pre-existing HGS asymmetries.

The design of device handles may also affect reliability along with HGS outputs, thus there appears need to uniformly set up devices for each participant. Most dynamometers are adjustable to the following five widths: 3.49, 4.76, 6.03, 7.30, and 8.57 cm; whereas customized cylindrical strain gauge dynamometers often have differing diameters (e.g. 2.54, 3.81, 5.08, 6.35, and 7.62 cm) (35). Studies have shown that grip widths and diameters between 3.81 and 5.08 cm are optimal for maximizing grip strength in adults (14, 35, 190). HGS was optimized, when individuals were permitted to self-select grip-width (diameter); 46 and 54% of the subjects selected handgrip diameters of 4.76 cm (position 2) and 6.03 cm (position 3), respectively (14). Interestingly, HGS measured at a width of 10% greater (HGS = 44.7 kg) than the self-selected (HGS = 45.2 kg) width was not significantly different, whereas HGS was significantly reduced using widths of 10% less (HGS = 43.6 kg) than the self-selected width (190). Therefore, it can be inferred that a grip width of half the distance between the index fingertip and the metacarpophalangeal flexion crease at the base of the thumb is optimal for achieving maximum HGS. As for reliability, there does not seem to be any notable difference between retest measures if handle positions are used consistently. However, the following factors should also be considered:

- HGS reliability observed for participants with a ratio showing greater length of palm than width (ICC = 0.92 - 0.95) has been reported as more stable than for female participants with more equal or square palm ratio (ICC = 0.48) (23);
- Devices with smooth handles, such as the Jamar, may be disadvantageous for assessing grip strength of each finger, nor permit a maximal measure for participants with smaller or sensitive hands. This in part is due to the dynamometer’s relatively non-adjustable and large handle positions and hard rigid grasping surface. Such factors may influence the ability for participants to reproduce maximal efforts.

Sport specific handgrip strength and force testing protocols

Although it is important for clinicians to establish globally standardized HGS testing procedures to ensure consistent and accurate measurements; it may also be beneficial and possibly more informative to sports coaches and athletes if strength and conditioning coaches and sports scientists develop sports specific HGS testing protocols. The majority of sports herein have utilized one of the standardized seated or standing position HGS assessment protocols (see Table 1) (43, 127). Subsequent discussions of sports specific HGS testing protocols have been divided into the following four categories: 1) hand-to-projectiles, 2) hand-to-implement, 3) hand-to-immovable apparatuses, and surfaces and 4) hand-to-hand combat.

Hand-to-projectile interactions in sport

Hand-to-projectile interactions can be defined as any action where the hand must apply force to an object causing projectile motion of the object, including, but not limited to, throwing (e.g. baseball, cricket, waterpolo, handball, American football, rugby, soccer, shot putt, discus, javelin and hammer throw), bowling (overarm and underarm), shooting (e.g. basketball and netball), and hitting (volleyball and Australian rules football). A number of these actions utilize a variation of the "precision grip" dependent on the action, size and shape of the object (177, 198). Intuitively assessing HGS utilizing a sports specific grip may provide a better representation of the athlete's "true" (sports specific) HGS. Tajika et al. (177) assessed handgrip and pinchgrip strength in high school baseball pitchers utilizing the standardized seated position recommended by the American Society of Hand Therapists. Considering that hand and pinch strength are relatively unrelated ($r^2 = 2\text{-}4\%$), the inclusion of the various pinch grips allows for a more comprehensive assessment of hand, finger and thumb strength of baseball pitchers (177). Tan et al. (178, 179) developed a similar and reliable protocol ($r = 0.91$) to measure Ten-pin bowling specific HGS, where only the fingers used in holding the bowling ball were tested. When compared to a conventional HGS test, only a *small* non-significant relationship (r^2 = 7%) was observed, which reiterates the importance of developing sport and object HGS testing protocols to better inform coaches and practitioners of the athlete's sport and object specific (e.g. shape, size, mass, texture and density) HGS.

Hand-to-implement interactions in sport

The "power grip" is also commonly utilized in sport when gripping cylindrical shaped implements and objects, such as clubs (golf), bats (baseball, softball, cricket), rackets (tennis, badminton, squash), sticks (field hockey, lacrosse, ice hockey), bars (weightlifting, powerlifting, strongman), and axes (lumberjack athletes) (198). The hand is the final link (i.e. terminal point of contact) along the kinetic chain where the generated forces and torques are transferred to the implement or object, hence the importance of handgrip function and strength to the above sports specific movements. The "power grip" more closely resembles the grip used during conventional standing and seated HGS testing protocols. One study found leather work gloves significantly reduced HGS (33 vs 43 kgf) in comparison to no gloves (142), which may be an important consideration for athletes that wear gloves during competition, such as golfers, baseball players and ice hockey players. One must also consider the shape, diameter, and mass of the implement, and/or object used in sport when determining how to affectively measure sports specific HGS.

To overcome the inherent limitation of maximum isometric HGS assessments, researchers have designed and examined HGF and pressure using specialized sensors during dynamic movements and sports specific actions, such as swinging a club, racket, bat, and stick (36, 89, 90, 92, 95, 121, 123, 152, 170, 202). Prior to dynamic human trials, the pressure and force sensing devices were calibrated and validated using a range of static and dynamic procedures. Komi et al. (92) assessed the static and dynamic validity and reliability of the following three sensors with mixed outcomes; F-Scan 9811 pressure sensors (measurement error = 6.7 ± 4.8%), flexiforce sensors (measurement error = 10.0 ± 3.5%), and quantum tunneling composite electrodes (measurement error = 13.0 ± 2.8%). Data were sampled at frequencies of 264 Hz, 640-1280 Hz, and 640-1280 Hz, respectively. Similar to the hand dynamometers, a range of known loads were used to calibrate the F-Scan (pressure = 310 kPa), flexiforce (range = 0.4 to 11.2 kg; $r^2 = 0.94$), and quantum tunneling composite (range = 0.4 to 11.2 kg; $r^2 = 0.95$) sensors. All three sensors were more accurate during the static tests (measurement error = 6.7-13.0%) in comparison to the dynamic tests (measurement error = 15-64%). Similar static validation findings using F-Scan (measurement error = 1.3-5.8%), resistive sensors (force measurement error < 2 N; $r^2 = 0.988$), and load cells ($r^2 > 0.994$) were also observed (7, 17, 89, 90, 152, 202).

During sports specific movement trials, sensor-sampling frequencies ranged from 100 to 2900 Hz depending on the sensor of interest. Within and between subject reliability of HGF produced during the different sports specific movement patterns were assessed using varying sample sizes (n = 2 to 28) across 4 to 32 trials depending on the study (Table 3). Researchers found that within-subject total HGF (CV < 10%), force at impact (CV < 5%), and the impulse ($r = 0.95$) to be reliable during the golf swing in male and female recreational, collegiate, and professional golfers, as measured using F-scan sensors sampled at 100 Hz and 264 Hz, respectively (95, 152). However, higher between-subject HGF variability (CV = 20-60%) was observed throughout the phases of the golf swing; the between-subject variability was also higher during the backswing (CV = 30-60%), and lower just prior to impact (CV = 20-30%). In varsity and professional tennis players, Knudson and White (90) observed poor within-subject HGF reliability at impact (CV = 27 ± 9%), and post-impact (CV = 69 ± 44%) when returning balls fired at 20 m/s from a ball machine. Knudson (89) also observed less within-subject variability in pre-impact (CV = 13-27%) and post-impact (CV = 15-29%) HGF during the one-handed backhand stroke under a similar testing protocol. Similarly, poor between-subject HGF reliability was observed in cricket batting pre-impact (CV = 31-32%), on-impact (CV = 23-51%), and post-impact (CV = 20-41%) with the ball bowled at a medium-fast pace; the within-subject reliability was not reported (169). Interestingly and as expected, HGF produced by skilled-elite (CV = 23 ± 8%) tennis players' were larger and less variable than their less skilled-subelite (CV = 33 ± 7%) counterparts.

The above observations indicate that the within-subject HGF produced during the golf swing are less variable and more reliable than the forehand and backhand tennis strokes in part due to the reactive nature of tennis (i.e. making contact with a moving object) in comparison to the non-reactive nature of golf (i.e. hitting a stationary ball). Another possible explanation is that larger vibration forces are experienced by the hands during a tennis stroke because of the length discrepancy between tennis rackets and golf clubs. Detailed analyses and interpretation of handgrip force-time signatures using accurate pressure and force sensors during dynamic sports specific actions could greatly improve current HGF diagnostics to optimize sport performance.

Hand-to-immovable apparatus or surface interactions in sport

High relative HGS and HGS endurance is required for climbing and gymnastics, where the athlete is moving his or her body around an immovable apparatus (e.g. rock-wall, mountain, parallel bars, uneven bars, and the pummel horse) for an extended period of time. A number of rock climbing studies have assessed maximum HGS (ICC = 0.93-0.96) and HGS endurance (ICC = 0.86-0.92) from a hanging position with the elbows flexed at 90^o and with the elbows fully extended overhead (5, 9, 102). Balas et al. (9) observed *moderate* (r = 0.49) and *very large* (r = 0.72) correlations between conventional HGS and hanging HGS endurance in elite male and female rock climbers, respectively. These highly reliable rock climbing specific maximum HGS and HGS endurance testing protocols can be implemented as possible indicators of rock-climbing ability, as discussed in the following section (Part 2). Amca et al. (5) developed laboratory based protocols similar to the previously mentioned hanging position utilizing a wall mounted force plate to measure maximum force (vertical, and antero-posterior) generated during rock-climbing specific grips (half-crimp and crimp grip); however, the reliability of these protocol were not reported. Detailed biomechanical assessments of hand and finger forces produced during climbing specific grips (e.g. crimp and slope grips) have also been measured using high frequency sampling (1024 Hz) strain gauge technology in trained climbers; the reliability of these assessments were not reported (135, 155). No research to date has been conducted on HGF measures during climbing and/or gymnastics events.

Hand-to-hand combat

In hand-to-hand combat sports, such as wrestling, judo, jiu-jitsu, and mixed martial arts, maximum HGS is important when pushing, pulling, throwing and controlling your opponent. Possessing a high level of HGS endurance is also believed to be important, if, and when the match/fight progresses into the later rounds (15, 30, 48). Therefore, it is recommended to include measures of maximum HGS and HGS endurance in the physical assessment battery of hand-to-hand combats sports. Hanging position HGS endurance protocols using judogi and kimono sleeves (ICC > 0.98) have been utilized in Judo (judokas) and Jiu Jitsu athletes to better assess sports specific HGS endurance of these two disciplines (45, 48). Bonitch-

Góngora et al. (15) implemented a novel HGS fatigue (endurance) protocol in judo athletes using the conventional position recommended by the American Society of Hand Therapist (43), where the athletes completed 8 consecutive maximum isometric contractions of 10 s with a 10 s rest between contractions. Significant reductions ($p = 0.000$) in HG torque were observed between the first and eighth contraction in elite male ($ES = 2.12$) and female ($ES = 1.38$) judo athletes. Dias et al. (30) also implemented a similar protocol consisting of a 10 s maximum isometric contraction utilizing a strain gauge dynamometer to measure peak force, time-to-peak force, impulse and fatigue in highly trained judokas. Judo combat can be characterized as a high-intensity intermittent sport requiring a combination of maximum strength and endurance during grip combat, where the ability to rapidly obtain and sustain a strong grip and pull or push the opponent is a desired attribute in judo athletes. A valid ($r = 0.78$) and reliable (ICC = 0.97) judo specific maximum HG pulling force protocol has also been developed using a specialized strain gauge, where the athletes gripped a judogi sleeve in a standing position with shoulder adducted, the elbow flexed at 90^o and the forearm in a neutral position (29, 72). While this is a measure of pulling strength and not a direct measure of HGS, the hand is only point of contact to apply and transfer force to the judogi sleeve. Again, no research to date has been conducted on HGF measures during any hand-to-hand combat sports.

Handgrip strength assessment recommendations

In summary, a variety of HGD's, strain gauges, and pressure sensors are available to practitioners to measure and monitor HGS and HGF under isometric and dynamic conditions. As dynamometers differ in manufacturing design, they produce different absolute measurements and therefore should not be used interchangeably. The reliability of HGS measures is dependent on the maintenance and calibration of the dynamometer; therefore, the servicing of equipment should be carefully considered and implemented by the practitioner. If various practitioners are to be involved in assessing participants, the inter-rater reliability for any protocol should be reported, and protocols refined.

A summary of HGS testing protocols is provided in Table 1, however we recommend practitioners consider the following and establish their own test-retest reliability for assessing HGS :

- The posture and position of shoulder, elbow, forearm and wrist are accurately described and replicated on each test occasion.
- At least three trials are performed with rest intervals of at least one-minute.
- Re-test reliability is assessed over three separate sessions, and examined using either the peak or average of the three trials of each testing occasion.
- The age, gender, hand-dominance, anthropometrics, and sport demographics of participants are reported along with ICC or test-retest correlations.
- The HG width setting chosen is noted along with the dynamometers specifications and manufacturer details.
- Conditions associated with testing such as participant observation, encouragement, nutrition or environment, are reported.

HGS dynamometry, as with any assessment tool, requires rigid adherence to protocols to provide robust and reliable performance monitoring.

INSERT TABLE 1 ABOUT HERE

More advanced laboratory based handgrip testing protocols have also been utilized to affectively assess isometric and dynamic HGF and torque in athletes (4, 33, 66, 68, 84, 89, 178). HGF testing protocols using specialized force and pressure sensors have also been implemented to accurately measure and monitor HGF during sports specific actions, such as swinging a club, bat, stick, or racket (Table 2). However, dynamic HGF protocols using advance technology may be less viable and practical than the previously mentioned protocols using commercially available HGD.

INSERT TABLE 2 ABOUT HERE

PART 2: HANDGRIP STRENGTH AND SPORT PERFORMANCE

Clinically, the function, assessment and rehabilitation of the hand and forearm are well-researched areas; however, the second part of this article will focus primarily on the relationship and effects of HGS to sport and athlete performance. During a number of sport specific movements, the hand is the only point of physical contact between the athlete and the implement and/or object, hence the functional importance of the hand to sport performance (198, 202). Young (198), describes and illustrates the differences between the "precision grip" used for grasping sphere shaped objects (e.g. balls) and the "power grip" used for grasping cylindrical shaped objects (e.g. clubs, bats, rackets, sticks and paddles). The majority of sports specific actions involving the hand utilize the precision grip, power grip, or a variation of these grips. HGS is believed to be an important attribute for throwing (e.g. baseball, softball, cricket, American football, European football, rugby, handball, water polo, javelin, hammer throw, discus, and shot put), bowling (i.e. overhand and underhand), punching, clinching, and grappling in hand-to-hand combat sports, paddling (e.g. row, canoe, and kayak), and swinging a racket, stick, bat, or club (e.g. cricket, baseball, golf, tennis, squash, lacrosse, field hockey and, ice hockey) (61, 66, 127, 163, 173, 200, 202). Other sports requiring a sufficient to high level of HGS may include: basketball, volleyball, rock climbing, swimming, sailing, riding/driving (e.g. horses, bulls, mountain bikes, motorcycles, and racecars), and strength athletes (e.g. weightlifting, powerlifting, and strongman).

On review of the available HGS literature at publication, the authors observed that some sports such as baseball, golf, climbing, swimming, water polo, wrestling, judo, handball, and tennis have had more research attention. In contrast, other sports where HGS is also believed to play a role in performance had minimal research attention, such as paddling sports (e.g. kayaking, rowing, and canoeing), hockey (ice and field), basketball, volleyball, riding (horses, bulls, bikes, and motorcycles), and driving (race cars). Due to the lack of studies investigating the relationship between HGS and performance in a number of sports, making definitive conclusions and recommendations for practitioners is problematic. Furthermore, there is a lack of longitudinal interventions constraining interpretations about causal relationships between training methods to improve HGS and performance outcomes. However, the studies presented in Tables 3 and 4, provide evidence to support, as well as refute the importance of and relationships between HGS and sport performance.

A large number of studies found that elite and successful athletes possessed greater HGS in comparison to their sub-elite and less successful counterparts (Table 3) supporting the relationship (Table 4) between HGS and the level of sporting ability (15, 28, 33, 52, 55, 56, 63, 87, 129, 143, 159). In contrast, some studies found minimal differences in HGS between elite and sub-elite athletes (27, 109, 132, 136, 148, 157, 199). However, closer examination of the included studies has provided some clarity and revealed a number of trends between HGS and performance across a range of sports. Subsequent discussions have been organized according to sport type as follows: 1) stick, club, bat, racket, and ball sports, 2) water sports, 3) climbing and gymnastics, 4) combat sports, and 5) strength disciplines.

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Handgrip Strength in Stick, Club, Bat, Racket and Ball Sports

This section will focus primarily on the relationships between HGS and the following sports specific actions: throwing (overhand and underhand) and bowling (overhand and underhand) a ball and swinging a stick, club, bat and racket. *Trivial* to *nearly perfect* correlations were observed between HGS and throwing velocity (r = 0.22-0.62), throwing energy (0.89-0.91), cricket bowling accuracy (r = 0.03), ten-pin bowling accuracy (r = -0.12-0.27), bat, club, and stick/puck speed (r = 0.31-0.85), bat energy (r = 0.88-0.90), fielding percentage (r = -0.09), and golf, field hockey, ice hockey, and lacrosse shot accuracy (r = -0.11-0.36) (3, 4, 6, 16, 18, 31, 51, 73, 78, 106, 107, 120, 134, 138, 164, 165, 172, 176, 178, 179, 189, 192, 193, 202). These findings suggest that HGS is more closely related to rotational movements requiring high torque, work and velocity generating abilities; whereas movements requiring a high amount of technical precision and accuracy appear to be less related to HGS. Similarly, once a threshold of HGS is attained, further competitive advantage may not be gained where the coordination and timing (e.g. bat, club, stick, and racket sports) of skilled actions is more important (174).

A number of studies also found other measures of upper and lower strength (e.g. shoulder rotation, torso rotation, lower back, chest, back squat, hang clean, pull-up, bent-over row, cable woodchop, and bench press), ballistic ability (e.g. medicine ball chest pass, rotational medicine ball throw, vertical, and lateral jumps), technical ability (e.g. shoulder, elbow and knee angles during wind-up, and release), and body composition (e.g. height, arm length, body mass, and lean body mass) to have *moderate* to *nearly perfect* associations (r = 0.34-0.95) with overhand bowling (cricket), throwing (baseball and softball), and bat and club velocity (3, 16, 50, 62, 73, 74, 86, 96, 101, 103, 117, 134, 137, 172, 173, 176, 192, 193, 197). It also appears that increased HGS is associated with greater upper strength, ballistic performance (r = 0.65), body mass (r = 0.50), lean body mass (r = 0.56-0.57), and height (r = 0.33) across a number of these sports (91, 129, 149, 177).

A comparison of professional baseball players revealed *trivial* and *moderate* non-significant HGS differences between the Major League Baseball (MLB©) and minor league baseball ("AAA" and "AA") players, respectively; whereas, *moderate* and *large* significant differences were observed between MLB players in comparison to "A" and rookie league players, respectively (76). Possibly indicating that there are minimal difference in HGS between the various groups of professional baseball players; where as a between study comparison revealed *very large* (*ES* = 2.16-4.77) differences in HGS between professional and amateur baseball players (76, 199). A similar trend was also observed in ice-hockey players; where elite collegiate male hockey players produced significantly *larger* HGS in comparison to sub-elite collegiate players. The elite players were also significantly taller and heavier, which may have contributed to the differences in HGS (129). *Trivial* to *very large* correlations were observed between HGS and shot (wrist and slap) velocity in male and female hockey players (4, 202). Alexander et al. (4) observed that body mass (r = 0.48) was more closely associated with slap shot velocity than HGS (r = 0.25) in elite male ice-hockey players. In support of the notion that HGS plays a role in shot velocity, Zane (202) observed that players with a high slap-shot velocity produced significantly greater HGS in comparison to their low-velocity counterparts.

A limited number of studies have investigated the effects of HGS training interventions on sports specific actions, such as throwing and swinging, therefore it is difficult to draw any definitive conclusions. However, two studies investigating the effects of resistance training supplemented with HGS and forearm training over 12 weeks found significantly greater improvements in forearm and HGS than the resistance training only group (175); similar *moderate* improvements in bat swing velocity (3.2 and 3.5%) were observed in both training groups (174). This indicates that performing additional resistance training designed to increase forearm and HGS did not further enhance bat-swing velocity in high school baseball players. Furthermore, an 8-week bat swing training study using a dynamic moment of inertia bat designed to reduce the moment of inertia during the initial stage of the swing, lead to significantly greater improvements in bat velocity (6.2%) in comparison to training with a standard bat (-2.1%) (99). Of note, 8-weeks of inertia bat training lead to *trivial* reductions (*ES* = -0.09) in right HGS and *moderate* improvements (*ES* = 0.44) in left HGS, respectively; whereas, the standard bat training lead to *large* reductions (*ES* = *-0.68* and -0.74) in right- and left- HGS. In summary, resistance training without additional HGS training is an effective means of improving HGS and bat swing velocity concurrently in high school baseball players; whereas, rotational inertia bat swing training is 2-fold more effective than resistance training at increasing bat swing velocity in baseball players. Other hand-to-implement sports, such as tennis, squash, and badminton could also potentially benefit from rotational velocity specific training using specialized equipment.

Handgrip Strength in Court Sports

Court sports where hand function and arguably HGS are of importance, include racket sports (e.g. tennis, squash and badminton), handball, volleyball, basketball, netball, and box lacrosse. In the majority of court sports, high torque and rotational velocity of the shoulder, arm, and wrist during overarm movements are desired attributes and a requirement for generating greater ball release velocities (185). Wagner et al. (185) observed that the overarm movements of serving a tennis ball, spiking a volleyball, and throwing a handball have similar but not identical proximal-to-distal sequencing of joint kinematics throughout the phases (i.e. cocking, accelerating and follow through), indicating that there is a general motor pattern in overarm movements. Hence the similar associations with the various predictive variables; such as *moderate* to *very large* correlations were observed between HGS, and ball/racket velocities during serving in tennis and volleyball players (r = 0.30-0.66), and throwing velocity in handball (r = 0.50-0.68) (24, 114, 133, 161, 182, 203). These findings further support the notion that HGS is an important attribute for athletes performing high rotational torque actions, such as overarm throwing, serving, and spiking actions, where the successful action of serving a volleyball and/or tennis ball depends on height of contact, ball direction (i.e. projection and trajectory), and release velocity .

Volleyball and handball playing ability (r = 0.78-0.90), and tennis ranking (r = 0.67-0.80) also appear to be strongly associated with HGS, sprint acceleration, jumping ability, and motor coordination (61, 114, 131, 132, 162), with the exception of Roetart et al. (144) whom found a *trivial* relationship between tennis ranking and HGS in junior male tennis players. To further support these relationships, elite handball athletes produced significantly greater HGS (MDiff = 30%) and muscle mass (MDiff = 17%) in comparison to their sub-elite counterparts (109). HGS is less of a discriminator between elite and sub-elite junior court based athletes, as may be expected based on the similarities in body mass and, in turn, muscle mass between elite and sub-elite youth athletes (132, 183).

Other strength (e.g. bench press strength and wrist, elbow, shoulder, and knee torque), ballistic (e.g. medicine ball throw distance, and bench throw velocity, and power), flexibility (e.g. shoulder and wrist), and anthropometric (e.g. body mass, lean mass, height, and arm span) measures were also *moderately* to *very largely* correlated (r = 0.31-0.85) with serving, spiking, and throwing velocity in tennis, volleyball, and handball athletes, respectively (24, 26, 114, 128, 160, 203). This indicates that multiple regression analyses that include two or more of the key variables (e.g. anthropometric, flexibility, strength, and ballistic ability) provide better predictive ability of serving and throwing velocity, as opposed to a single variable (24, 26, 132).

HGS was also found to be *very largely* correlated with free throw shooting accuracy (r = 0.76) of semi-professional basketball players in a non-fatigued state; however, in a fatigued state (post-training) a non-significant relationship was observed (104). The authors suggest this was due to varying within group adaptations to training load, which was likely due to individual variations in fitness and recovery rates. With the exception of the above study, movements and actions requiring a high amount of precision and accuracy appear to be less related to HGS, such as points/game and assists/game in basketball (113), or tennis stroke technique and accuracy (i.e. service, forehand, backhand, down line, cross-court, and serve placement) (128, 144). Shot accuracy and precision in tennis players was more closely associated (r = 0.34-0.57) with other strength measures, such as knee and shoulder torque (128).

Handgrip strength in field sports

Field sports, where hand function is of importance include field hockey (i.e. passing and shooting), field lacrosse (i.e. defending, passing and shooting), rugby (i.e. passing, gripping, fending and tackling), Australia Rules Football, Gaelic Football, American football (throwing, gripping, fending and tackling) and European football (i.e. during the throw-in and for the keeper). In field sports, the hand applies a gripping force to the implement (i.e. stick), object (i.e. ball) or body (i.e. opposition) for the purpose of holding or restraining, which is often a quasi-dynamic or an isometric application of HGF. Anecdotally, grasping and holding a stick or object in sport will require less HGF in comparison to the HGF required for gripping, holding, restraining and/or tackling an opposing player. However, there is minimal HGF research on field sport specific actions to support these claims.

In contact field sports, such as American football, *moderate* to *very large* differences (*ES* = 0.47 – 1.10) were observed between elite and sub-elite male athletes (159, 168). Straub (168) also observed significantly larger HGS in the older more experienced professional players (age = 28 yrs) in comparison to the younger less experienced collegiate players (age = 20 yrs). Williford et al. (195) also observed that heavier linemen possessed much greater levels of overall strength (*ES* = 1.10 – 1.94) than the lighter backs. Similarly, older and heavier professional rugby league players possessed significantly greater overall strength (*ES* = 1.78) in comparison to the younger lighter sub-elite state league players (8). Based on the positive associations (r = 0.46 – 0.58) between HGS and overall strength and body mass in rugby and American football athletes (180), it can be inferred that field sport athletes possessing greater overall strength should also possess greater HGS.

The strength differences within a homogenous group of professional athletes appears to be much less. Shields et al. (159) investigating the strength differences within a team of professional American football players found *small* to *moderate* non-significant differences in HGS and overall strength (i.e. upper and lower body strength) between veteran starters and non-starters. To further support these findings, *trivial* to *small* negative and positive correlations were observed between HGS and player rankings within samples of collegiate and professional American football teams; indicating that HGS is unrelated to playing performance within a given cohort of American football athletes (168). These findings are also in agreement with trends observed in elite male field hockey players and professional male baseball players (76, 157).

As expected, other performance markers, such as sprinting, change-of-direction, and aerobic capacity were unrelated to HGS in field sport athletes (r = -0.11 to 0.16); with the exception of a group of adolescent (age = 11-17 yrs) European football players (80). In this study, sprint and change-of-direction ability were significantly correlated with HGS, and the majority of physical performance measures were significantly correlated with age. These findings indicate HGS may be a covariate of overall physical ability and age in developing youth athletes.

A number of actions performed in field sports (i.e. passing, throwing, and shooting) also require high torques and rotational (angular) velocities for generating greater ball release velocities. During these actions, the hand is the terminal point (i.e. last point) of contact along the kinetic chain just prior to release or impact, therefore optimal function of the hand is vital to applying force and pressure to the implement or ball in their execution (198). The timing and sequencing of the applied force during these actions is arguably more important than the maximum amount of HGF an athlete can generate. The *low* correlations observed between maximum HGS and passing and shooting accuracy in field sports, reinforces the notion that HGS is not the determining factor in highly coordinated skilled actions (107, 157, 189).

Handgrip forces in action

The coordination, timing and sequencing of force, and pressure applied by the hand to an object (i.e. ball), or implement (i.e. bat, stick, racket, or club) during the various stages of a given sports specific movement pattern (i.e. swinging an implement and/or throwing an object) is fundamental to understanding the importance of the hand to sports performance. The laws of linear, angular, and projectile motion state that angular velocity, point of contact or point/height of release, impact force, release trajectory, and linear release velocity are the key performance indicators for swinging an implement and throwing an object . Accurate assessment of handgrip forces along with other kinematic (i.e. angular acceleration and angular velocity) and kinetic (i.e. torque) variables contributing to the resultant performance indicators are key to understanding the mechanisms of these actions. Based on the handgrip force-time signatures during the golf swing, cricket bat swing, baseball bat swing, hockey slap-shot and wrist-shot, and tennis forehand, and backhand, the following trends were observed (17, 19, 36, 90, 92, 95, 152, 169, 202):

- Low total handgrip forces were applied during the backswing
- High total handgrip forces were applied during the acceleration phase
- Reduced total handgrip forces at impact
- A spike in force occurring immediately prior to and a second spike in force occurring immediately post-impact (with the exception of cricket batting)

Furthermore, the amount of force and pressure used to grip a ball, stick, racket, club, bat, bar, disc, or handle is inversely proportional to wrist range of motion; and in turn the amount of applied force varies throughout the stages of a given movement pattern. This mechanical relationship between force application and joint range-of-motion during complex dynamic movements in sport may help explain the conjecture in the literature regarding the relationship between isometric HGS and sports performance. This information suggests that the timing and sequencing of the force applied to an implement or object by the hand (palm, digits, and thumb) in sport is of greater importance than the magnitude of applied force alone.

Handgrip Strength in Water Sports

In water sports, the hand is often directly (i.e. swimming) or indirectly (i.e. gripping a paddle, oar, or rudder) the last bodily point of contact within the kinetic chain propelling oneself through the water; hence the importance of the hand to performance in most, if not all, water sports. In competitive swimmers, *trivial* non-significant *to very large* significant correlations were observed between HGS and freestyle swim performance (12, 25, 32, 57, 58, 147, 200). The majority of these participants were comprised of competitive youth and teenage athletes (82%). In light of these mixed findings, stronger correlations were observed between HGS and sprint swim performance (r = 0.18 – 0.82; distance ≤ 100m) in comparison to swim endurance performance (r = 0.01 – 0.65; distance ≥ 200m) in youth and teenage swimmers. To further reinforce the notion a regression analysis revealed that HGS may have a greater contribution to sprint swim performance, Zampagni et al. (200, 201) found HGS explained 52% of the variance in 50m freestyle swim performance and only 15% of the variance in 800m swim performance of elite male and female masters swimmers (n = 135). Therefore, HGS could possibly be used as an affective sprint distance performance predictor in competitive masters' swimmers. Based on the physical characteristics of swimmers it has been suggested that maximum HGS along with other upper and lower body strength measures play a greater role in sprint swim versus endurance swim performance (58). Other single and multiple (combined) measures of strength (e.g. tethered swim force, upper arm, shoulder, and abdominal flexion) along with horizontal jump performance, aerobic, and anaerobic capacity, anthropometry (e.g. height, arm span, and foot length), and flexibility (ankle and shoulder range of motion) are of equal or greater importance to predicting swim performance (i.e. via linear and multivariate regression analyses) in adolescent, teenage and adult swimmers (32, 147, 200).

It is also suspected that HGS would also play a part in a number of other water sport disciplines such as, surfing, kayaking, canoeing, paddle boarding, rowing, whitewater slalom (canoe and kayak), and sailing. In support of this claim, Secher (156) reported a significant correlation (r = 0.44) between HGS and rowing performance, as well as a *very large* significant difference in HGS between elite international and club level male rowers. Hamano et al. (68) also found that HGS was *largely* to *very largely* correlated with average power during 2 min maximum effort canoe and kayak ergometer sprints in elite flatwater canoers (r = 0.75) and kayakers (r = 0.65), respectively. *Large* to *very large* correlations were also observed between kayak/canoe ergometer performance and a number of anthropometric measures (e.g. body mass, lean muscle mass, and chest, waist, and arm girth), bench press strength, and lower body knee extension torque. These findings further reinforce the notion that possessing the aforementioned anthropometric and physical performance qualities are beneficial to excelling in water sports.

There is a sufficient volume of research investigating the relationships between HGS and throwing velocity in water polo athletes (1, 40-42, 108). Water polo can be described as a contact team sport with an emphasis on swimming, jumping, throwing, blocking, pushing and holding (42). The overhand throwing action used for 90% of all passes and shots in water polo is similar to that of other throwing sports (e.g. handball, baseball, and cricket). The main point of difference is that water polo athletes must generate the majority of their force and torque with their upper body as opposed to land based sports where force is transferred from the ground through the kinetic chain. *Moderate* to *large* correlations were observed between HGS and throwing velocity in elite water polo athletes, accounting for 13 to 36% of the variance in throwing velocity (1, 40-42). The findings indicate that certain anthropometric characteristics (r = 0.68 – 0.95), such as limb length, height, lean muscle mass, and somatotype along with throwing technique may be greater predictors of throwing velocity in water polo athletes (1, 41, 42). No water sport HGS comparative studies (elite vs. sub-elite) were available.

Handgrip Strength in Climbing and Gymnastics

Athletes partaking in climbing and gymnastics (i.e. rings and bars) arguably require a high amount of relative HGS and HGS endurance to successfully compete in their respective disciplines. Limited research is available on HGS and performance in gymnastics athletes; however, one study found *very large* correlation (r = 0.81) between HGS and HGS endurance in ring athletes (146). Due to the limited number of articles published on gymnastics athletes, subsequent discussions will focus on climbing athletes. In climbers, *large* to *very large* correlations were observed between maximum relative HGS (i.e. HGS relative to body mass), crimp grip strength, pinch grip strength, and rock climbing ability (r = 0.55 - 0.94) (9, 53, 116, 191).

Following a similar trend to previous sections, climbing performance is related to the interactions of multiple variables (e.g. upper and lower body strength, anthropometry, body composition and flexibility) rather than a single predictive measure (115, 116, 187). Studies comparing elite to sub-elite adult male rock climbers observed *large* to *very large* differences

(*ES* = 1.20 - 3.86) in HGS between groups (9, 64). More pronounced HGS differences were observed between elite and sub-elite female rock climbers (*ES* = 2.00 - 4.90), while similar differences were also observed between elite and sub-elite female athletes in other sports (i.e. field hockey, judo, and ten-pin bowlers) (9, 15, 63, 87, 136, 148, 179, 187). Based on the correlation and comparative findings, there is strong evidence to suggest that possessing a high amount of relative HGS is advantageous to competing and excelling in the sport of climbing as well as gymnastics (i.e. rings and bars).

Handgrip Strength in Combat Sports

Success in combat sports, such as boxing, mixed martial arts and wrestling is multifaceted and requires high levels of technical, tactical, physical and psychological ability to compete and excel at any level (47, 148); and cannot be predicted by a single physical parameter. Franchini et al. (49) found no significant relationships between HGS and technical actions (e.g. throws, holds, locks or chokes) in elite judokas. Opposing this finding, *moderate* and *very large* relationships have been observed between HGS and wrestling success (r = 0.41) and boxing competition ranking (r = 0.87), respectively (66, 122). In support of the positive relationship between HGS and combat sport performance, a pooled effect size comparison of elite to sub-elite athletes indicates that elite male athletes possess higher HGS in comparison to their sub-elite counterparts (*ES* = 0.91). Furthermore, elite adult male wrestlers (*ES* = 1.17) and judokas (*ES* = 2.23-3.07) produced much larger HGS in comparison to sub-elite adult male wrestlers and judokas (33, 122). These elite combat sport athletes also possessed greater overall strength (i.e. bench press, squat and pull-up strength) and ballistic abilities (i.e. vertical jump, horizontal jump, sprinting, and shot putt performance); further supporting the notion that HGS is a covariate of overall strength.

Similarly, junior male high school wrestlers with a high winning percentage possessed significantly greater HGS (*ES* = 3.33) than wrestlers with a low winning percentage (143). The pooled data also suggests that HGS has a *large* positive effect (*ES* = 0.70) on wrestling and judo performance in junior male athletes. However, the high variability in the magnitude of differences (ES_{range} = -0.61 to 0.83) in HGS between studies comparing elite to sub-elite junior male combat sport athletes provides some evidence to refute the importance of HGS to performance (15, 27, 28, 55, 148). Demirkan et al. (27) observed *trivial* to *moderate* non-significant HGS differences between junior male (age = 16.2 – 16.7 yrs) elite and sub-elite wrestlers. Sanchez et al. (148) also observed *trivial* to *moderate* non-significant HGS differences between gold, silver, bronze, and non-medaling junior male (age = 15 – 19 yrs) judokas, whereas Garcia-Pallares et al. (55) using a slightly older cohort of junior male wrestlers (age = 17.5 – 19.6 yrs), found that the elite wrestlers exhibited *moderate* non-significant to *largely* significant greater HGS capabilities versus their sub-elite counterparts. These findings suggest that the magnitude of difference in HGS between elite and sub-elite adult male wrestlers and judokas is larger than the HGS differences in junior elite and sub-elite male wrestlers and judokas. A possible explanation for this phenomenon could be that the differences in overall strength (i.e. maximum upper and lower body strength) between the elite and sub-elite athletes within the junior male population is less than the overall strength differences within the adult male population.

The differences in HGS between elite and sub-elite female combat sport athletes was more pronounced than their male counterparts. A pooled effect size analysis revealed *very large* HGS differences (*ES* = 1.57) between elite and sub-elite junior female wrestlers and judokas (15, 56, 148). The accentuated HGS differences between elite and sub-elite combat sport athletes within the female population may be in part attributed to the differences in age, overall strength and training experience (56).

Following a similar trend to the previously discussed sports and athletic disciplines, combat sport studies have observed *moderate* to *very large* overall strength differences between elite and sub-elite combat sports athletes (27, 55, 56, 122). Additionally, there are *moderate* to *very large* relationships between combat sport performance and other strength (r = 0.40), anaerobic (r = 0.65-0.91), aerobic (r = 0.81), and body composition (r = -0.70 to -0.87) measures (49, 66, 122). In summary, elite combat sport athletes appear to possess greater overall maximum strength, explosive strength, lower body fat percentages, and greater aerobic and anaerobic capacity in comparison to amateur and sub-elite combat sport athletes.

Handgrip Strength in Strength Athletes

The literature indicates that there is a strong linear relationship between maximum HGS and maximum upper and lower body strength in non-strength sport athletes. This relationship in strength athletes is subsequently discussed. Athletes participating in the following disciplines are classified as strength athletes: Olympic weightlifters, powerlifters, and strongman competitors. Schoffstall et al. (153) observed *nearly perfect* correlations ($r \geq 0.97$) between HGS and powerlifting strength (i.e. bench press, squat and deadlift) in male and female raw competitive powerlifters; whereas *small* to *moderate* correlations (r = 0.31-0.41) were observed between HGS and powerlifting strength in equipped powerlifters (i.e. permitted to wear wrist wraps, knee wraps and supportive powerlifting suits). It appears that HGS is a good indicator of total strength in competitive raw powerlifters, but not equipped powerlifters. The importance of HGS in equipped powerlifting is likely reduced due to the use of wrist wraps, knee wraps and powerlifting suits designed to better stabilize the athlete during the various lifts; whereas in raw powerlifting wraps and suits are not permitted likely increasing the HGS demands during the respective lifts. A relatively small sample size was used in this study; therefore, caution is advised when interpreting these relationships.

In support of these relationships, Fry et al. (52) observed *large* differences in HGS (*ES* = 0.93) between elite and sub-elite junior Olympic weightlifters. The elite group was also more impulsive (i.e. vertical jump) and stronger across all lifts (i.e. snatch, clean and jerk, front squat, back squat and bench press). The above study, suggests that a regression analysis incorporating the following testing battery, vertical jump ability, HGS, body composition, flexibility, and kinesthetic awareness can be used to accurately differentiate elite from sub-elite junior male weightlifters. These findings align with previous recommendations, in that multiple regression analyses that include two or more important dependent variables will provide a more accurate and informative prediction of athletic ability. Of note, the elite junior lifters herein possessed strength levels (clean = 125 kg, back squat = 173 kg, bench press = 111 kg) similar to that of adult male team sport athletes. Caution must be advised when interpreting these findings, as only a small cohort of strength athletes were examined due to the lack of current research examining HGS in strength athletes.

CONCLUSION

A HGD, as with any assessment tool, requires rigid adherence to clinical, practical, and/or newly developed sports specific HGF and pressure testing protocols to provide robust and reliable monitoring of athletes. Based on the large number of HGS studies discussed in this review, key generalizations, and sports specific recommendations for strength and conditioning coaches have been provided.

In general, HGS appears to be an attribute of elite athletes and a covariate of overall upper and lower body strength, impulsive ability (i.e. sprinting and jumping), body mass, lean muscle mass, age and training experience (i.e. training age). HGS also seems to be related to movement patterns (i.e. most rotational movements) that utilize the kinetic chain (i.e. the summation of forces and torques initiated and distributed in sequence from large to small muscle groups) to generate large torques and angular velocities, where the hand is the terminal (i.e. last) point of contact prior to impact and/or release. Furthermore, the timing and sequencing of the force applied to an implement (i.e. bat, stick, club, racket and bar) or object (i.e. ball) by the hand in sport is arguably of greater importance than the magnitude of applied force alone. The transfer of force and torque during any complex kinetic chain movement sequence is dependent on several factors including technique (i.e. coordination and sequencing), strength, anthropometry and flexibility.

By way of contrast, movement patterns requiring a high degree of accuracy and relatively low release velocities are poorly related to maximum isometric HGS. These movement patterns may include but are not limited to shooting and passing accuracy, chipping and putting accuracy, tennis stroke placement, fielding performance (i.e. baseball and cricket) and bowling score. Similarly, once a threshold of HGS is attained, such as within a group of elite athletes, further competitive advantage may not be gained in sports where timing (e.g. bat, club, stick and racket sports) and/or the scoring of skilled maneuvers is part of the technical and tactical strategy (e.g. judo, wrestling, boxing and mixed martial arts) (179). It is also not surprising that aerobic fitness measures share less common variance with HGS, as remarkable muscle mass is not observed or needed in sports requiring such attributes.

In summary, HGS training is conceivably of importance to enhancing the performance of a number of gross motor movement patterns in sports and athletic disciplines involving the hand. By simply increasing overall upper and lower body strength and increasing muscle mass through various resistance-training interventions, an athlete's maximum isometric HGS should increase. However, improving an athletes ability to effectively apply force to an object or implement during a given sport specific movement pattern is multifactorial. These factors include technical ability (i.e. movement coordination, sequencing and timing), physical capacity (i.e. strength, flexibility, neuromuscular function and reaction time), body composition anthropometry, and tactical ability (i.e. reading and reacting to the opposition). Therefore, it is recommended that the sport scientist, strength and conditioning coach and technical (i.e. skills) coach:

- Identify the key physical, technical and tactical factors that determine proficiency and mastery of a given movement pattern;
- Develop a specific battery of tests to effectively measure and monitor improvements in these key factors;
- Train the key movement patterns and muscles groups to improve and master a given sports specific movement pattern.

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References

1. Abraldes J, Canossa S, Soares S, Fernandes R, and Garganta J. Relationship between hand grip strength and shot speed in different competitive level water polo players, in: *National Strength and Conditioning Association International Conference*. San Antonio, Spain, 2014, p S143.
2. Agbuga B, Konukman F, and Yilmaz I. Prediction of upper body strength by using grip strength test in division II American college football players' grip strength. *Hac J Sport Sci* 20: 16-23, 2009.
3. Albert J, Szymanski D, and Standley B. Relationship between changes in physiological characteristics and softball- specific variables of NCAA division I softball players. *J Strength Cond Res* 22: 83-84, 2008.
4. Alexander J, Haddow J, and Schultz G. Comparison of the ice hockey wrist and slap shots for speed and accuracy. *Res Q Ex Sport* 34: 259-266, 1963.
5. Amca AM, Vigouroux L, Aritan S, and Berton E. Effect of hold depth and grip technique on maximal finger forces in rock climbing. *J Sports Sci* 30: 669-677, 2012.
6. Amritashish B and Shiny R. Anthropometric and physical variables as predictors of off-spin performance in cricket: a multiple regression study. *Int J Sports Sci Fit* 5: 314-322, 2015.
7. Bachus KN, DeMarco AL, Judd KT, Horwitz DS, and Brodke DS. Measuring contact area, force, and pressure for bioengineering applications: using Fuji Film and TekScan systems. *Med Eng Phys* 28: 483-488, 2006.
8. Baker DG and Newton RU. Comparison of lower body strength, power, acceleration, speed, agility, and sprint momentum to describe and compare playing rank among professional rugby league players. *J Strength Cond Res* 22: 153-158, 2008.
9. Balas J, Pecha O, Martin A, and D. C. Hand-arm strength and endurance predictors of climbing performance. *Eur J Sport Sci* 12: 16-25, 2012.
10. Beaton DE, O'Driscoll SW, and Richards RR. Grip strength testing using the BTE work simulator and the Jamar dynamometer: a comparative study. Baltimore Therapeutic Equipment. *J Hand Surg* 20: 293-298, 1995.
11. Bellace JV, Healy D, Besser MP, Byron T, and Hohman L. Validity of the Dexter Evaluation System's Jamar dynamometer attachment for assessment of hand grip strength in a normal population. *J Hand Ther* 13: 46-51, 2000.
12. Blanksby B, Bloomfield J, Ponchard M, and Ackland TR. The relationship between anatomical characteristics and swimming performance in state age group championship competitors. *J Swim Res* 2: 30-36, 1986.
13. Blomkvist AW, Andersen S, de Bruin ED, and Jorgensen MG. Isometric hand grip strength measured by the Nintendo Wii Balance Board - a reliable new method. *BMC Musculo Dis* 17: 56, 2016.
14. Boadella JM, Kuijer PP, Sluiter JK, and Frings-Dresen MH. Effect of self-selected handgrip position on maximal handgrip strength. *Arch Phys Med Rehab* 86: 328-331, 2005.
15. Bonitch-Góngora JG, Almeida F, Padial P, Bonitch-Domínguez JG, and Feriche B. Maximal isometric handgrip strength and endurance differences between elite and non-elite young judo athletes. *Sci Mar Arts* 9: 239-248, 2013.
16. Bonnette R, Spaniol F, Melrose D, Ocker L, Paluseo J, and Szymanski D. The relationship between rotational power, bat speed, and batted-ball velocity of NCAA division I baseball players *J Strength Cond Res* 22: 112-113, 2008.
17. Broker JP and Ramey MR. A new method for measuring grip force and its distribution during the golf swing. *Annual Rev Golf Coach*: 121-134, 2007.
18. Brown SJ, Nevill AM, Monk SA, Otto SR, Selbie WS, and Wallace ES. Determination of the swing technique characteristics and performance outcome relationship in golf driving for low handicap female golfers. *J Sports Sci* 29: 1483-1491, 2011.

19. Budney D and Bellow D. Evaluation of golf club control by grip pressure measurement
in: *Science and Golf*. London: E & FN Spon, 1990 pp 30-35.

20. Busca B, Morales J, Solana-Tramunt M, Miro A, and Garcia M. Effects of jaw clenching while wearing a customized bite-aligning mouthpiece on strength in healthy young men. *J Strength Cond Res* 30: 1102-1110, 2016.

21. Cadenas-Sanchez C, Sanchez-Delgado G, Martinez-Tellez B, Mora-Gonzalez J, Lof M, Espana-Romero V, Ruiz JR, and Ortega FB. Reliability and validity of different models of tkk hand dynamometers. *Am J Occ Ther* 70: 1-9, 2016.

22. Chidley JB, MacGregor AL, Martin C, Arthur CA, and Macdonald JH. Characteristics explaining performance in downhill mountain biking. *Int J Sports Physiol Perf* 10: 183-190, 2015.

23. Clerke AM, Clerke JP, and Adams RD. Effects of hand shape on maximal isometric grip strength and its reliability in teenagers. *J Hand Ther* 18: 19-29, 2005.

24. Cohen DB, Mont MA, Campbell KR, Vogelstein BN, and Loewy JW. Upper extremity physical factors affecting tennis serve velocity. *Am J Sports Med* 22: 746-750, 1994.

25. Dalamitros AA, Manou V, and Pelarigo JG. Laboratory-based tests for swimmers: methodology, reliability, considerations and relationship with front-crawl performance. *J Hum Sport Ex* 9: 172-187, 2014.

26. Debanne T and Laffaye G. Predicting the throwing velocity of the ball in handball with anthropometric variables and isotonic tests. *J Sports Sci* 29: 705-713, 2011.

27. Demirkan E, Koz M, Kutlu M, and Favre M. Comparison of physical and physiological profiles in elite and amateur young wrestlers. *J Strength Cond Res* 29: 1876-1883, 2015.

28. Demirkan E, Unver R, Kutlu M, and Koz M. The comparison of physical and physiological characteristics of junior elite wrestlers. *University J Physical Ed Sport Sci* 6: 138-144, 2012.

29. Detanico D, Arins FB, Pupo JD, and Santos SGD. Strength parameters in judo athletes: An approach using hand dominance and weight categories. *Hum Mov* 13: 330-336, 2012.

30. Dias JA, Wentz M, Kulkamp W, Mattos D, Goethel N, and Junior NB. Is the handgrip strength performance better in judokas than in non-judokas? *Sci Sports* 27: e9-14, 2012.

31. Doan BK, Newton RU, Kwon YH, and Kraemer WJ. Effects of physical conditioning on intercollegiate golfer performance. *J Strength Cond Res* 20: 62-72, 2006.

32. Douda HT, Toubekis AG, Georgio C, Gourgoulis V, and Tokmakidis SP. Predictors of performance in pre-pubertal and pubertal male and female swimmers. Presented at International Symbosium on Biomechanics and Medicine in Swimming, Oslo, Norway, 2010.

33. Drid P, Casals C, Mekic A, Radjo I, Stojanovic M, and Ostojic SM. Fitness and anthropometric profiles of international vs. national judo medalists in half-heavyweight category. *J Strength Cond Res* 29: 2115-2121, 2015.

34. Dunwoody L, Tittmar HG, and McClean WS. Grip strength and intertrial rest. *Percept Motor Skills* 83: 275-278, 1996.

35. Edgren CS, Radwin RG, and Irwin CB. Grip force vectors for varying handle diameters and hand sizes. *Hum Factors* 46: 244-251, 2004.

36. Eggeman GW and Noble ML. Design and testing of a baseball- bat transducer. *Exp Tech* 9: 20-23, 1985.

37. El-Sais WM and Mohammad WS. Influence of differeent testing postures on hand grip strength. *Eur Sci J* 10: 290-301, 2014.

38. Espana-Romero V, Ortega FB, Vicente-Rodriguez G, Artero EG, Rey JP, and Ruiz JR. Elbow position affects handgrip strength in adolescents: validity and reliability of Jamar, DynEx, and TKK dynamometers. *J Strength Cond Res* 24: 272-277, 2010.

39. Essendrop M, Schibye B, and Hansen K. Reliability of isometric muscle strength tests for the trunk, hands and shoulders. *Int J Ind Erg* 28: 379-387, 2001.

40. Ferragut C, Abraldes J, Manchado C, and Vila H. Water polo throwing speed and body composition: an analysis by playing positions and opposition level. *J Hum Sport Ex* 10: 81-94, 2015.

41. Ferragut C, Abraldes J, Vila H, Rodriguez N, Argudo F, and Fernandes R. Anthropometry and throwing velocity in elite water polo by specific playing positions. *J Hum Kinet* 27: 31-44, 2011.

42. Ferragut C, Vila H, Abraldes J, Argudo F, Rodriguez N, and Alcaraz PE. Relationship among maximal grip, throwing velocity and anthropometric parameters in elite water polo players. *J Sports Med Phys Fit* 51: 26-32, 2011.

43. Fess EE and Moran CA. Grip Strength, in: *Clinical Assessment Recommendations* Chicago: American Society of Hand Therapists, 1992.

44. Fike M and Rousseau E. Measurement of adult hand strength: a comparions of two instruments. *Occup Ther J Res* 2: 43-49, 1982.

45. Follmer B, Dellagrana RA, Franchini E, and Diefenthaler. Relationship of kimono grip strength tests with isokinetic parameters in jiu-jitsu athletes. *Braz J Kinanthrop Hum Perform* 17: 575-582, 2015.

46. Fong PW and Ng GY. Effect of wrist positioning on the repeatability and strength of power grip. *Am J Occ Ther* 55: 212-216, 2001.

47. Franchini E, Del Vecchio FB, Matsushigue KA, and Artioli GG. Physiological profiles of elite judo athletes. *Sports Med* 41: 147-166, 2011.

48. Franchini E, Miarka B, Matheus L, and Vecchio FBD. Endurance in judogi grip strength tests: comparison between elite and non-elite judo players. *Sci Mar Arts* 7: 1-4, 2011.

49. Franchini E, Takito MY, and Bertuzzi RCM. Morphological, physiological and technical variables in high-level college judoists. *Sci Mar Arts* 1: 1-7, 2005.

50. Freeston JL, Carter T, Whitaker G, Nicholls O, and Rooney KB. Strength and power correlates of throwing velocity on subelite male cricket players. *J Strength Cond Res* 30: 1646-1651, 2016.

51. Fry A, Honnold D, Hudy A, Roberts C, Gallagher P, Vardiman P, and Dellasega C. Relationships between muscular strength and batting performances in collegiate baseball athletes. *J Strength Cond Res* 25: 19-20, 2011.

52. Fry AC, Ciroslan D, Fry MD, LeRoux CD, Schilling BK, and Chiu LZ. Anthropometric and performance variables discriminating elite American junior men weightlifters. *J Strength Cond Res* 20: 861-866, 2006.

53. Gajeswski J, Hubner-Woziak E, Tomaszewski P, and Sienkiewicz-Dianzenza E. Changes in handgrip force and blood lactate as response to simulated climbing competition. *Biol Sport* 26: 14-21, 2009.

54. Gallo-Salazar C, Areces F, Abian-Vicen J, Lara B, Salinero JJ, Gonzalez-Millan C, Portillo J, Munoz V, Juarez D, and Del Coso J. Enhancing physical performance in elite junior tennis players with a caffeinated energy drink. *Int J Sports Physiol Perf* 10: 305-310, 2015.

55. Garcia-Pallares J, Lopez-Gullon JM, Muriel X, Diaz A, and Izquierdo M. Physical fitness factors to predict male Olympic wrestling performance. *Eur J Appl Physiol* 111: 1747-1758, 2011.

56. Garcia Pallares J, Lopez-Gullon JM, Torres-Bonete MD, and Izquierdo M. Physical fitness factors to predict female Olympic wrestling performance and sex differences. *J Strength Cond Res* 26: 794-803, 2012.

57. Garrido N and Silva A. High level swimming performance and its relation to non-specific parameters: A cross-sectional study on maximum handgrip isometric strength. *Percept Motor Skills* 114: 936-948, 2012.

58. Geladas ND, Nassis GP, and Pavlicevic S. Somatic and physical traits affecting sprint swimming performance in young swimmers. *Int J Sports Med* 26: 139-144, 2005.

59. Gerodimos V. Reliability of handgrip strength test in basketball players. *J Hum Kinet* 31: 25-36, 2012.

60. Gerodimos V and Karatrantou K. Reliability of maximal handgrip strength test in pre-pubertal and pubertal wrestlers. *Pediatr Exerc Sci* 25: 308-322, 2013.

61. Girard O and Millet GP. Physical determinants of tennis performance in competitive teenage players. *J Strength Cond Res* 23: 1867-1872, 2009.

62. Gordon BS, Moir GL, Davis SE, Witmer CA, and Cummings DM. An investigation into the relationship of flexibility, power, and strength to club head speed in male golfers. *J Strength Cond Res* 23: 1606-1610, 2009.

63. Grant S, Hasler T, Davies C, Aitchison TC, Wilson J, and Whittaker A. A comparison of the anthropometric, strength, endurance and flexibility characteristics of female elite and recreational climbers and non-climbers. *J Sports Sci* 19: 499-505, 2001.

64. Grant S, Hynes V, Whittaker A, and Aitchison T. Anthropometric, strength, endurance and flexibility characteristics of elite and recreational climbers. *J Sports Sci* 14: 301-309, 1996.

65. Guerra RS and Amarla TF. Comparison of hand dynamometers in elderly people. *J Nut Health Age* 13: 907-912, 2009.

66. Guidetti L, Musulin A, and Baldari C. Physiological factors in middleweight boxing performance. *J Sports Med Phys Fit* 42: 309-314, 2002.

67. Gurer B and Yildiz M. Investigation of sport rock climbers' handgrip strength. *Biol Ex* 11: 55-71, 2015.

68. Hamano S, Ochi E, Tsuchiya Y, Muramatsu E, Suzukawa K, and Igawa S. Relationship between performance test and body composition/physical strength characteristic in sprint canoe and kayak paddlers. *J Sports Med* 6: 191-199, 2015.

69. Hamilton A, Balnave R, and Adams R. Grip strength testing reliability. *J Hand Ther* 7: 163-170, 1994.

70. Hamilton GF, McDonald C, and Chenier TC. Measurement of grip strength: validity and reliability of the sphygmomanometer and jamar grip dynamometer. *J Orthop Sports Phys Ther* 16: 215-219, 1992.

71. Haward BM and Griffin MJ. Repeatability of grip strength and dexterity tests and the effects of age and gender. *Int Arch Occup Environ Health* 75: 111-119, 2002.

72. Heinisch HD, Knoll K, Kindler M, and Haupt H. Development and evaluation of a judo-specific grip strength-test. Presented at International Judo Research Symposium, Rio de Janeiro, 2013.

73. Heitman RJ, Pugh SF, Erdmann JW, and Kovaleski JE. Measurement of upper and lower body strength and its relationship to underhand pitching speed. *Percept Motor Skills* 90: 1139-1144, 2000.

74. Hellstrom J. The relation between physical tests, measures, and clubhead speed in elite golfers. *Int J Sports Sci Coach* 3: 85-92, 2008.

75. Hobbs SJ, Baxter J, Broom L, Rossell LA, Sinclair J, and Clayton HM. Posture, flexibility and grip strength in horse riders. *J Hum Kinet* 42: 113-125, 2014.

76. Hoffman JR, Vazquez J, Pichardo N, and Tenenbaum G. Anthropometric and performance comparisons in professional baseball players. *J Strength Cond Res* 23: 2173-2178, 2009.

77. Hopkins WG. Linear models and effect magnitudes for research, clinical and practical applications. *Sportsci* 14: 49-57, 2010.

78. Hughes SS, Lyons BC, and Mayo JJ. Effect of grip strength and grip strengthening exercises on instantaneous bat velocity of collegiate baseball players. *J Strength Cond Res* 18: 298-301, 2004.

79. Innes E. Handgrip strength testing: a review of the literature. *Aust Occup Ther J* 46: 120-140, 1999.

80. James RS, Thake CD, and Birch S. Relationships between measures of physical fitness change when age dependent bias is removed in a group of young male soccer players. *J Strength Cond Res* Ahead of Print, 2016.

81. Johnston DW, Nicholls ME, Shah M, and Shields MA. Nature's experiment? Handedness and early childhood development. *Demography* 46: 281-301, 2009.

82. Jones LA. The assessment of hand function: a critical review of techniques. *J Hand Surg* 14: 221-228, 1989.

83. Josty IC, Tyler MP, Shewell PC, and Roberts AH. Grip and pinch strength variations in different types of workers. *J Hand Surg Br* 22: 266-269, 1997.

84. Kamimura T and Ikuta Y. Evaluation of grip strength with a sustained maximal isometric contraction for 6 and 10 seconds. *J Rehab Med* 33: 225-229, 2001.

85. Keeton S. Fitness level and success in female intercollegiate equestrian athletes, in: *Science in Health Promotion*. Oklahoma: Oklahoma State University, 2005.

86. Keogh JW, Marnewick MC, Maulder PS, Nortje JP, Hume PA, and Bradshaw EJ. Are anthropometric, flexibility, muscular strength, and endurance variables related to clubhead velocity in low- and high-handicap golfers? *J Strength Cond Res* 23: 1841-1850, 2009.

87. Keogh JW, Weber CL, and Dalton CT. Evaluation of anthropometric, physiological, and skill-related tests for talent identification in female field hockey. *Can J Appl Physiol* 28: 397-409, 2003.

88. Kilic I and Binboga M. Investigation of structural and biomotoric features of young volleyball players and determining the position by discriminant analysis. *Sci Mov Health* 12: 142-153, 2012.

89. Knudson D. Forces on the hand in the tennis one-handed backhand. *Int J Sport Biomech* 7: 282-292, 1991.

90. Knudson DV and White SC. Forces on the hand in the tennis forehand drive: Application of force sensing resistors. *Int J Sport Biomech* 5: 324-331, 1989.

91. Koley S, Yadav M, and Sandhu J. Estimation of hand grip strength and its association with some anthropometric traits in cricketers of amritsar, punjab, india. *Internet J Biol Anthropol* 3: 1-7, 2008.

92. Komi E, Roberts J, and Rothberg S. Evaluation of thin, flexible sensors for time-resolved grip force measurement. *J Mech Eng Sci* 221: 1687-1699, 2008.

93. Kramer JF, Nusca D, Bisbee L, MacDermid J, Kemp D, and Boley S. Forearm pronation and supination: reliability of absolute torques and nondominant/dominant ratios. *J Hand Ther* 7: 15-20, 1994.

94. Lagerstrom C and Nordgren B. On the reliability and usefulness of methods for grip strength measurement. *Scandinavian Journal of Rehabilitation Medicine* 30: 113-119, 1998.

95. Langlais SM and Broker JP. Grip pressure distributions and associated variability in golf: a two-club comparison. *Sports Biomech* 13: 109-122, 2014.

96. Lewis AL, Ward N, Bishop C, Maloney S, and Turner AN. Determinants of club head speed in PGA professional golfers. *J Strength Cond Res* 30: 2266-2270, 2016.

97. Leyk D, Gorges W, Ridder D, Wunderlich M, Ruther T, Sievert A, and Essfeld D. Hand-grip strength of young men, women and highly trained female athletes. *Eur J Appl Physiol* 99: 415-421, 2007.

98. Lindstrom-Hazel D, Kratt A, and Bix L. Interrater reliability of students using hand and pinch dynamometers. *Am J Occ Ther* 63: 193-197, 2009.

99. Liu C, Liu YC, Kao YC, and Shiang TY. Effects of training with a dynamic moment of inertia bat on swing performance. *J Strength Cond Res* 25: 2999-3005, 2011.

100. Llaurens V, Raymond M, and Faurie C. Why are some people left-handed? an evolutionary perspective. *Philos Trans Royal Soc B* 364: 881-894, 2009.

101. Loock H, Grace J, and Semple S. Association of selected physical fitness parameters with club head speed and carry distance in recreational golf players. *Int J Sports Sci Coach* 8: 769-777, 2013.

102. Lopez-Rivera E, Jose J, and Gonzalez-Badillo JJ. The effects of two maximum grip strength training methods using the same effort duration and different edge depth on grip endurance in elite climbers. *Sports Tech* 5: 100-110, 2012.

103. Lowe H, Szymanski DJ, Bankston BL, Braswell MT, Britt AT, Gilliam ST, Herring AL, Holloway BT, Lowe DW, Potts JD, Szymanski JM, and Till ME. Relationship between body composition and bat swing velocity of college softball players. *J Strength Cond Res* 24, 2010.

104. Lupo C. Anthropometric, strength, session-RPE, and shoot performance evaluations in sub-elite male italian basketball players. *Ital J Anat Emb* 120: 204, 2015.

105. Lusardi MM and Bohannon RW. Hand grip strength: comparability of measurements obtained with a Jamar dynamometer and a modified sphygmomanometer. *J Hand Ther* 4: 117-122, 1991.

106. Mangine GT, Hoffman JR, Vazquez J, Pichardo N, Fragala MS, and Stout JR. Predictors of fielding performance in professional baseball players. *Int J Sports Physiol Perf* 8: 510-516, 2013.

107. Marsh DW, Richard LA, Verre AB, and Myers J. Relationships among balance, visual search, and lacrosse-shot accuracy. *J Strength Cond Res* 24: 1507-1514, 2010.

108. Martinez JG, Vila MH, Ferragut C, Noguera MM, Abraldes JA, Rodriguez N, Freeston J, and Alcaraz PE. Position-specific anthropometry and throwing velocity of elite female water polo players. *J Strength Cond Res* 29: 472-477, 2015.

109. Massuca LM, Fragoso I, and Teles J. Attributes of top elite team-handball players. *J Strength Cond Res* 28: 178-186, 2014.

110. Massy-Westropp N, Rankin W, Ahern M, Krishnan J, and Hearn TC. Measuring grip strength in normal adults: reference ranges and a comparison of electronic and hydraulic instruments. *J Hand Surg* 29: 514-519, 2004.

111. Mathiowetz V. Comparison of Rolyan and Jamar dynamometers for measuring grip strength. *Occup Ther Int* 9: 201-209, 2002.

112. Mathiowetz V, Weber K, Volland G, and Kashman N. Reliability and validity of grip and pinch strength evaluations. *J Hand Surg* 9: 222-226, 1984.

113. McGill SM, Andersen JT, and Horne AD. Predicting performance and injury resilience from movement quality and fitness scores in a basketball team over 2 years. *J Strength Cond Res* 26: 1731-1739, 2012.

114. Melrose D, Bohling M, Spaniol F, and Bonnette R. Physiological and performance characteristics of adolescent club volleyball players *J Strength Cond Res* 20: e20, 2006.

115. Mermier CM, Janot JM, Parker DL, and Swan JG. Physiological and anthropometric determinants of sport climbing performance. *Br J Sports Med* 34: 359-365; discussion 366, 2000.

116. Mitchell AC, Bowhay A, and Pitts J. Relationship between anthropometric characteristics of indoor rock climbers and top roped climbing performance. *J Strength Cond Res* 25: S94-95, 2011.

117. Miyaguchi K and Demura S. Relationship between upper-body strength and bat swing speed in high-school baseball players. *J Strength Cond Res* 26: 1786-1791, 2012.

118. Moran CA. Anatomy of the hand. *Phys Ther* 69: 1007-1013, 1989.

119. Murugan S, Pate D, Prajapati K, Ghoghari M, and Patel P. Grip strength changes in relation to different body postures, elbow and forearm positions. *Int J Physiother Res* 1: 116-121, 2013.

120. Nakata H, Nagami T, Higuchi T, Sakamoto K, and Kanosue K. Relationship between performance variables and baseball ability in youth baseball players. *J Strength Cond Res* 27: 2887-2897, 2013.

121. Nikonovas A, Harrison AJ, Hoult S, and Sammut D. The application of force-sensing resistor sensors for measuring forces developed by the human hand. *J Eng Med* 218: 121-126, 2004.

122. Nikooie R, Cheraghi M, and Mohamadipour F. Physiological determinants of wrestling success in elite Iranian senior and junior Greco-Roman wrestlers. *J Sports Med Phys Fit*, 2015.

123. Noble L and Eggeman GW. Baseball bat instrumentation for the measurement of hand forces. *J Biomech* 15: 341, 1982.

124. Oxford KL. Elbow positioning for maximum grip performance. *J Hand Ther* 13: 33-36, 2000.

125. Parvatikar VB and Mukkannavar PB. Comparative study of grip strength in different positions of shoulder and elbow with wrist in neutral and extension positions. *J Ex Sci Physiother* 5: 67-75, 2010.

126. Peolsson A, Hedlund R, and Oberg B. Intra- and inter-tester reliability and reference values for hand strength. *Journal of Rehabilitation Medicine* 33: 36-41, 2001.

127. Pereira HM, Menacho MO, Takahashi RH, and Cardoso JR. Handgrip strength evaluation on tennis players using different recommendations. *Braz J Sports Med* 17: 184-188, 2011.

128. Perry AC, Wang X, Feldman BB, Ruth T, and Signorile J. Can laboratory-based tennis profiles predict field tests of tennis performance? *J Strength Cond Res* 18: 136-143, 2004.

129. Peterson BJ, Fitzgerald JS, Dietz CC, Ziegler KS, Ingraham SJ, Baker SE, and Snyder EM. Division I hockey players generate more power than division III players during on- and off-ice performance tests. *J Strength Cond Res* 29: 1191-1196, 2015.

130. Peynircioglu ZF, Thompson JL, and Tanielian TB. Improvement strategies in free-throw shooting and grip-strength tasks. *J Gen Psych* 127: 145-156, 2000.

131. Phulkar A. Relationship of selected strength and flexibility measures to playing ability in handball. *Int J Health Sports Phys Ed* 2: 24-26, 2014.

132. Pion JA, Fransen J, Deprez DN, Segers VI, Vaeyens R, Philippaerts RM, and Lenoir M. Stature and jumping height are required in female volleyball, but motor coordination is a key factor for future elite success. *J Strength Cond Res* 29: 1480-1485, 2015.

133. Pugh SF, Kovaleski JE, Heitman RJ, and Gilley WF. Upper and lower body strength in relation to ball speed during a serve by male collegiate tennis players. *Percept Motor Skills* 97: 867-872, 2003.

134. Pugh SF, Kovaleski JE, Heitman RJ, and Pearsall AW. Upper and lower body strength in relation to underhand pitching speed by experienced and inexperienced pitchers. *Percept Motor Skills* 93: 813-818, 2001.

135. Quaine F and Vigouroux L. Maximal resultant four fingertip force and fatigue of the extrinsic muscles of the hand in different sport climbing finger grips. *Int J Sports Med* 25: 634-637, 2004.

136. Razman R, Cheong JPG, Abas WAB, and Osman NA. Anthropometric and strength characteristics of tenpin bowlers with different playing abilities. *Biol Sport* 29: 33-38, 2012.

137. Read PJ, Lloyd RS, De Ste Croix M, and Oliver JL. Relationships between field-based measures of strength and power and golf club head speed. *J Strength Cond Res* 27: 2708-2713, 2013.

138. Reed J, Szymanski D, Albert J, Hawthorne D, Hsu HS, Skinner C, and Tatum J. Relationship between physiological performance variables and baseball/softball specific variables of novice college students. *J Strength Cond Res* 22: 111-112, 2008.

139. Richards LG. Posture effects on grip strength. *Arch Phys Med Rehab* 78: 1154-1156, 1997.

140. Richards LG, Olson B, and Palmiter-Thomas P. How forearm position affects grip strength. *Am J Occ Ther* 50: 133-138, 1996.

141. Roberts HC, Denison HJ, Martin HJ, Patel HP, Syddall H, Cooper C, and Sayer AA. A review of the measurement of grip strength in clinical and epidemiological studies: towards a standardised approach. *Age Ageing* 40: 423-429, 2011.

142. Rock KM, Mikat RP, and Foster C. The effects of gloves on grip strength and three-point pinch. *J Hand Ther* 14: 286-290, 2001.

143. Roemmich JN and Frappier JP. Physiological determinants of wrestling success in high school athletes. *Pediatr Exerc Sci* 5: 134-144, 1993.

144. Roetert EP, Garrett GF, Brown SW, and Camaione DN. Performance profiles of nationally ranked junior tennis players. *J App Sport Sci Res* 6: 225-231, 1992.

145. Ruiz-Ruiz J, Mesa JL, Gutierrez A, and Castillo MJ. Hand size influences optimal grip span in women but not in men. *J Hand Surg* 27: 897-901, 2002.

146. Ruprai RK, Tajpuriya SV, and Mishra N. Handgrip strength as determinant of upper body strength/physical fitness: a comparative study among individuals performing gymnastics (ring athletes) and gymnasium (powerlifters). *Int J Med Sci Pub Health* 5: 1167-1171, 2016.

147. Saavedra JM, Escalante Y, and Rodriguez FA. A multivariate analysis of performance in young swimmers. *Pediatr Exerc Sci* 22: 135-151, 2010.

148. Sánchez AG, Domínguez AS, Turpin JAP, Tormo JMC, and Llorca CS. Importance of hand-grip strength as an indicator for predicting the results of competitions of young judokas. *Sci Mar Arts*: 3, 2011.

149. Sathya P, Kadhiravan V, Ramakrishnan K, and Ghodake A. Association between hand grip strength and shoulder power in intercollegiate cricket players. *Int J Innov Res Sci Eng Tech* 5: 3085-3091, 2016.

150. Saunders PU, Pyne DB, Telford RD, and Hawley JA. Reliability and variability of running economy in elite distance runners. *Med Sci Sports Exerc* 36: 1972-1976, 2004.

151. Schick MG, Brown L, Coburn J, Beam W, Schick E, and Dabbs C. Physiological profile of mixed martial artists. *Medicina Sportiva* 14: 182-187, 2010.

152. Schmidt E, Roberts J, and Rothberg S. Time-resolved measurements of grip force during a golf shot. *Eng Sport* 6, 2006.

153. Schoffstall J, Morrison SD, Kozlik B, and Boswell B. Grip strength and powerlifting performance, in: *Southeastern Chapter of the American College of Sports Medicine Regional Conference*. 2010.

154. Schreuders T, A. R. , Roebroeck M, E. , Goumans J, van Nieuwenhuijzen JF, Stijnen TH, and Stam HJ. Measurement error in grip and pinch force measurements in patients with hand injuries. *Physical Therapy* 83: 806, 2003.

155. Schweizer A. Biomechanical properties of the crimp grip position in rock climbers. *J Biomech* 34: 217-223, 2001.

156. Secher NH. Isometric rowing strength of experienced and inexperienced oarsmen. *Med Sci Sports* 7: 280-283, 1975.

157. Sharma A, Tripathi V, and Koley S. Correlations of anthropometric characteristics with physical fitness tests in Indian professional hockey players. *J Hum Sport Ex* 7: 698-705, 2012.

158. Shechtman O, Gestewitz L, and Kimble C. Reliability and validity of the DynEx dynamometer. *J Hand Ther* 18: 339-347, 2005.

159. Shields CL, Jr., Whitney FE, and Zomar VD. Exercise performance of professional football players. *Am J Sports Med* 12: 455-459, 1984.

160. Singh AB and Behera S. Relationship of anthropometric characteristics and kinematic variables with spiking of volleyball players. *J Ed Prac* 4: 165-171, 2013.

161. Smart J, McCurdy K, Miller B, and Pankey R. The effect of core training on tennis serve velocity. *J Strength Cond Res* 25: S103-104, 2013.

162. Smith DJ, Roberts D, and Watson B. Physical, physiological and performance differences between Canadian national team and universiade volleyball players. *J Sports Sci* 10: 131-138, 1992.

163. Spaniol F. Baseball athletic test: a baseball specific test battery. *Strength Cond J* 31: 26-29, 2009.

164. Spaniol F, Bonnette R, and Melrose D. Physiological predictors of bat speed and batted-ball velocity in NCAA division I baseball players *J Strength Cond Res* 20: e25, 2006.

165. Spaniol F, Bonnette R, and Melrose D. The relationship between grip strength and bat speed of adolescent baseball players *J Strength Cond Res* 21: e19-20, 2007.

166. Stephens JL, Pratt N, and Michlovitz S. The reliability and validity of the Tekdyne hand dynamometer: Part II. *J Hand Ther* 9: 18-26, 1996.

167. Stephens JL, Pratt N, and Parks B. The reliability and validity of the Tekdyne hand dynamometer: Part I. *J Hand Ther* 9: 10-17, 1996.

168. Straub WF. Grip strength of college and professional football players. *Ergonomics* 22: 1185-1194, 1979.

169. Stretch R. A biomechanical analysis of the double, in: *Science and Racket Sports*. T Reilly, M Hughes, A Lees, eds.: Taylor & Francis, 1994, pp 107-112.

170. Stretch RA, Bartlett R, and Davids K. A review of batting in men's cricket. *J Sports Sci* 18: 931-949, 2000.

171. Su CY, Lin JH, Chien TH, Cheng KF, and Sung YT. Grip strength in different positions of elbow and shoulder. *Arch Phys Med Rehab* 75: 812-815, 1994.

172. Szymanski D, Beiser EJ, Basset K, Till ME, and Szymanski J. Relationship between sports performance variables and bat swing velocity of collegiate baseball players. *J Strength Cond Res* 25: S122, 2011.

173. Szymanski DJ, DeRenne C, and Spaniol FJ. Contributing factors for increased bat swing velocity. *J Strength Cond Res* 23: 1338-1352, 2009.

174. Szymanski DJ, McIntyre JS, Szymanski JM, Molloy JM, Madsen NH, and Pascoe DD. Effect of wrist and forearm training on linear bat-end, center of percussion, and hand velocities and on time to ball contact of high school baseball players. *J Strength Cond Res* 20: 231-240, 2006.

175. Szymanski DJ, Szymanski JM, Molloy JM, and Pascoe DD. Effect of 12 weeks of wrist and forearm training on high school baseball players. *J Strength Cond Res* 18: 432-440, 2004.

176. Szymanski J, Szymanski D, Albert J, Reed J, Hemperley C, Hsu HS, Moore R, Potts J, Turner J, and Winstead R. Relationship between physiological characteristics and baseball-specific variables of high school baseball. *J Strength Cond Res* 22: 110-110, 2008.

177. Tajika T, Kobayashi T, Yamamoto A, Shitara H, Ichinose T, Shimoyama D, Okura C, Kanazawa S, Nagai A, and Takagishi K. Relationship between grip, pinch strengths and anthropometric variables, types of pitch throwing among Japanese high school baseball pitchers. *Asian J Sports Med* 6: e25330, 2015.

178. Tan B, Aziz AR, and Chuan TK. Correlations between physiological parameters and performance in elite ten-pin bowlers. *J Sci Med Sport* 3: 176-185, 2000.

179. Tan B, Aziz AR, Teh KC, and Lee HC. Grip strength measurement in competitive ten-pin bowlers. *J Sports Med Phys Fit* 41: 68-72, 2001.

180. Tong RJ and Wood GL. A comparison of upper body strength in collegiate rugby union players, in: *World Congress of Science and Football*. T Reilly, J Bangsbo, M Hughes, eds. Cardiff, Wales: Taylor & Francis, 1995, pp 16-21.

181. Trossman PB and Li PW. The effect of the duration of intertrial rest periods on isometric grip strength performance in young adults. *Occup Ther J Res* 9: 362-378.

182. Tsakalou L, Kotsampouikidou Z, Papa M, and Zapartidis I. Handgrip strength and ball velocity of young male and female handball players
J Phys Ed Sport 15: 800-804, 2015.

183. Ulbricht A, Fernandez-Fernandez J, Mendez-Villanueva A, and Ferrauti A. Impact of fitness characteristics on tennis performance in elite junior tennis players. *J Strength Cond Res* 30: 989-998, 2016.

184. Verma SK. Assessment of physical variables of drag flick performance in field hockey. *Int J Phys Ed* 7: 78-80, 2014.

185. Wagner H, Pfusterschmied J, Tilp M, Landlinger J, von Duvillard SP, and Muller E. Upper-body kinematics in team-handball throw, tennis serve, and volleyball spike. *Scand J Med Sci Sports* 24: 345-354, 2014.

186. Waldo BR. Grip strength testing. *Strength Cond J* 18: 32-35, 1996.

187. Wall CB, Starek JE, Fleck SJ, and Byrnes WC. Prediction of indoor climbing performance in women rock climbers. *J Strength Cond Res* 18: 77-83, 2004.

188. Ward C and Adams J. Comparative study of the test-re-test reliability of four instruments to measure grip strength in a healthy population. *Br J Hand Ther* 12: 48-54, 2007.

189. Wassmer DJ and Mookerjee S. A descriptive profile of elite U.S. women's collegiate field hockey players. *J Sports Med Phys Fit* 42: 165-171, 2002.

190. Watanabe T, Owashi K, Kanauchi Y, Mura N, Takahara M, and Ogino T. The short-term reliability of grip strength measurement and the effects of posture and grip span. *J Hand Surg* 30: 603-609, 2005.

191. Watts P, Newbury V, and Sulentic J. Acute changes in handgrip strength, endurance, and blood lactate with sustained sport rock climbing. *J Sports Med Phys Fitness* 36: 255-260, 1996.

192. Weimer B, Halet K, and Anderson T. Relationship of strength variables to bat velocity in college baseball and softball players. *Missouri J Health Phys Ed Rec Dance* 17: 53-59, 2007.

193. Wells GD, Elmi M, and Thomas S. Physiological correlates of golf performance. *J Strength Cond Res* 23: 741-750, 2009.

194. Werle S, Goldhahn J, Drerup S, Simmen BR, Sprott H, and Herren DB. Age- and gender-specific normative data of grip and pinch strength in a healthy adult Swiss population. *J Hand Surg Eur* 34: 76-84, 2009.

195. Williford H, Kirkpatrick J, Scharff-Olson M, Blessing D, and Wang N. Physical and performance characteristics of successful high school football players. *Am J Sports Med* 22: 859-862, 1994.

196. Wimer B, Dong RG, Welcome DE, Warren C, and McDowell TW. Development of a new dynamometer for measuring grip strength applied on a cylindrical handle. *Med Eng Phys* 31: 695-704, 2009.

197. Wu T, Wu P, and Tsai Y. The relationship between strength, trunk rotation movements and ball speed in high school golfers. *Med Sci Sports Exerc* 39: S477, 2007.

198. Young RW. Evolution of the human hand: the role of throwing and clubbing. *J Anat* 202: 165-174, 2003.

199. Yu JH and Lee GC. Comparison of shoulder range of motion, strength, and endurance in amateur pitchers practicing repetitive overhead throwing. *Isokinet Exerc Sci* 21: 135-140, 2013.

200. Zampagni ML, Casino D, Benelli P, Visani A, Marcacci M, and De Vito G. Anthropometric and strength variables to predict freestyle performance times in elite master swimmers. *J Strength Cond Res* 22: 1298-1307, 2008.

201. Zampagni ML, Casino D, Visani A, Martelli S, Benelli P, Marcacci M, and De Vito G. Influence of age and hand grip strength on freestyle performances in master swimmers. Presented at International Symposium on Biomechanics in Sport, Austria, 2006.

202. Zane L. Force Measures at the Hand-Stick Interface during Ice Hockey Slap and Wrist Shots, in: *Department of Physical Education and Kinesiology*. Montreal, Canada: McGill, 2012, p 129.

203. Zapartidis I, Palamas A, Papa M, Tsakalou L, and Kotsampouikidou Z. Relationship among anthropometric characteristics, handgrip strength and throwing velocity in adolescent handball players. *J Physical Ed Sports Manage* 3: 127-139, 2016.

Table 1. Handgrip strength testing protocols

Positions	**Protocol**	**ICC**
Seated Positions (9, 13, 30, 34, 35, 38, 43, 46, 65, 69, 84, 93, 98, 110, 112, 119, 124, 127, 140, 158, 167, 181, 188, 190)	**Dynamometer**: hydraulic, spring, strain gauge, cylinder pneumatic, Wii balance board **Grip Breadth**: 2nd – 5th handle position (3.89 – 8.58 cm) **Grip Type**: Whole hand **Shoulder**: i) adducted, ii) flexed at 90^o, iii) flexed at 180^o **Elbow**: i) 90^o flexion, ii) extended **Forearm**: i) neutral, ii) pronated, iii) supinated **Wrist**: i) 0-30^o extension ii) neutral iii) ulnar deviation 0-15^o; radial deviation 0-15^o **Trials**: 1-3 x 3-10 s MVIC per hand **Rest**: 15-120 s between trials **Output**: mean and/or peak (kg, N, Pa) **Retest**: 1 to 7 days to assess reliability	0.69-0.99
Standing Positions (31, 38, 66, 119, 125, 127, 133, 171, 179, 190, 196)	**Dynamometer**: hydraulic, spring, strain gauge, pneumatic **Grip Breadth**: 2nd – 3rd handle position (4.76-6.03cm), cylinder, judogi sleeve **Grip type**: i) whole hand, ii) middle, ring finger and thumb **Shoulder**: i) adducted, ii) flexed at 90^o, iii) flexed at 180^o **Elbow**: i) flexed at 90^o ii) extended, **Forearm**: i) neutral, ii) pronated, iii) supinated **Wrist**: 0-30^o extension ii) neutral **Trials**: 1-3 x 2-5 s MVIC per hand **Rest**: 60-120 s between trials **Output**: peak and/or mean (kg, N, Pa) **Retest**: 0-2 days	0.90-0.99
Supine Positions (119, 190)	**Dynamometer**: hydraulic, spring **Grip Breadth**: 2nd – 4th handle position **Shoulder**: i) adducted **Elbow**: i) 90^o flexion, ii) extended, **Forearm**: i) neutral, ii) pronated, iii) supinated **Wrist**: 0-30^o extension **Trials**: 1-3 x 2-5 s MVIC per hand **Rest**: 60 s between trials **Output**: peak and mean (kg or N) **Retest**: none	NA
Hanging Positions (5, 9, 45, 48, 64, 102)	**Apparatus:** Pull-up bar, ledge (1-4 cm), judogi sleeve, strain gauge, force plate **Grip Type:** Overhand **Grip Width:** shoulder width **Shoulders:** i) flexed at 180^o; ii) flexed at 90^o; iii) 110^o flexion and 60^o horizontal abduction **Elbows:** i) flexed at 90^o, ii) extended, iii) flexed at 70^o **Forearms:** pronated **Wrist:** i) neutral, ii) 15-30^o extension **Trials:** i) 1-3 trials, ii) increase load in 5-10 kg increments, iii) 3 x MVIC **Rest:** 0 to 90 s **Output:** i) endurance time (s), ii) maximum load (kg) 5 s hold, iii) maximum vertical downward force (N) **Retest:** none	0.86-0.99

ICC = interclass correlation coefficient; MVIC = maximum voluntary isometric contraction; NA= not available

Table 2. Handgrip dynamic force testing protocols

Sport – Action	**Protocol**	**CV%**
Golf - Club Swing (17, 19, 92, 95, 152)	**Sensor**: Tekscan 9811 F-Scan (100-264 Hz), Quantum Tunnelling composite (1280 Hz), Flexiforce (640 Hz) video (60-200 Hz), sound (500 Hz) **Club Specifications**: 7-Iron and driver **Sample size range**: 2 to 28 **Trials**: 4-10 off a rubber tee or artificial turf **Rest**: Not specified **Outputs**: force-time signature, impact force, post-impact force, impulse **Retest**: None **Reliability**: Poor between subject (CV = 20-70%), good within subject (CV < 10%; ICC > 0.90).	5-60%
Baseball - Bat Swing (36, 123)	**Sensor**: strain gauge transducer (NA), video (50 Hz) **Bat Specifications**: 35 in, 31 oz Easton Big Barrel aluminum bat **Sample size range**: 1 **Procedures:** Pitcher throws medium-fast balls at ~36 m/s **Trials**: Not specified **Rest**: Not specified **Outputs**: force-time signatures **Retest**: None **Reliability**: Not reported	NA
Cricket – Bat Swing (169)	**Sensor**: strain gauge transducer **Bat Specifications**: Standard size short-handle cricket bat (Slazenger Inc.) **Sample size range**: 14 **Procedures:** Bowler bowls medium-fast balls at ~36 m/s **Trials**: Not specified **Rest**: Not specified **Outputs**: force-time signatures, pre-impact force, impact force, post-impact force **Retest**: None **Reliability**: Not reported	NA
Tennis - Racket Swing (89, 90)	**Sensor**: Force sensing resistors and load cells (1000 and 2900 Hz). **Racket Specifications**: Midsize Pro-Kennex racket **Sample size range**: 7 - 12 **Swing types:** forehand and backhand **Trials**: 10-32 strokes hit (balls projected by ball machine at 20 m/s) **Rest**: Not specified **Outputs**: pre-impact force, impact force, post-impact force **Retest**: None **Reliability**: Poor within- subject reliability during the forehand (CV = 21-140%); better within-subject reliability during the backhand (CV = 22 – 34%)	21-140%
Ice Hockey - Stick Shot (202)	**Sensor**: Piezoresistive sensors (1000 Hz) **Stick Specifications**: Carbon fibre (Bauer Hockey Corp.): 77 flex, 87 flex, and 102 flex **Sample size range**: 41 **Swing types:** slap-shot and wrist-shot **Trials**: 5 wrist shots, 5 slap shots **Rest**: Not specified **Outputs**: force-time signature, impact force, post-impact, impulse **Retest**: None **Reliability**: ± 10 N	NA

CV% = coefficient of variation represented as a percentage; NA = not available

Table 3. Handgrip strength differences between elite and sub-elite athletes

Sport	**Reference**	**n-sex**	**Age (yrs)**	**Level**	**Comparison**	**HGS (kgf)**	**Hand**	***ES***	*p≤0.05*
Baseball	Hoffman et al. (76)	62 M	28.7±4.2	MLB	MLB vs	110.0±16.0	R+L		
		52 M	26.8±2.7	AAA	AAA	115.6±12.6	R+L	-0.44	No
		50M	24.9±2.2	AA	AA	111.6±12.7	R+L	-0.13	No
		84 M	22.9±2.1	A	A	105.2±12.6	R+L	0.38	Yes
		90 M	21.3±2.5	Rookie	Rookie league	103.5±12.5	R+L	0.52	Yes
	Yu and Lee (199)	14 M	27.1±1.92	Amateur	3 yrs pitching vs.	38.8±3.4	D30^0		
		14 M	8.3±2.4		2 years	42.6±8.2	D30^0	-0.46	No
		14 M	27.7±2.8		1 year	42.7±5.8	D30^0	-0.54	No
					3 yrs pitching vs.	40.5±3.4	D90^0		
					2 years	43.7±8.7	D90^0	-0.37	No
					1 year	42.3±6.1	D90^0	-0.30	No
					3 yrs pitching vs.	40.5±2.1	D180^0		
					2 years	44.0±7.5	D180^0	-0.47	No
					1 year	40.4±6.1		0.02	No
Bowling	Razman et al. (136)	10 M	23.6±3.9	Elite	Elite vs.	7.10±1.95	Pinch	-0.12	No
		7 M	20.6±2.4	Subelite	Subelite	7.33±1.85	Pinch		
		8 F	22.4±5.4	Elite	Elite vs.	6.62±1.55	Pinch	1.42	No
		5 F	20.6±4.0	Subelite	Subelite	5.04±1.11	Pinch		
Climbing	Balas et al. (9)	136 M	24.7±NA	3-11$_{UIAA}$	9-11 $_{UIAA}$ vs	0.79±0.07	D/BM		
					7-9 $_{UIAA}$	0.72±0.09	D/BM	0.78	NA
					6-7 $_{UIAA}$	0.67±0.10	D/BM	1.20	NA
					3-5 $_{UIAA}$	0.57±0.10	D/BM	2.20	NA
		69 F	26.0±NA	3-11$_{UIAA}$	9-11 $_{UIAA}$ vs	0.72±0.07	D/BM		
					7-9 $_{UIAA}$	0.60±0.06	D/BM	2.00	NA
					6-7 $_{UIAA}$	0.52±0.06	D/BM	3.33	NA
					3-5 $_{UIAA}$	0.45±0.07	D/BM	3.86	NA
	Grant et al. (63)	10 F	31.3±5.0	Elite	Elite vs	34.4±1.2	R		
		10 F	24.1±4.0	Novice	Recreational	29.5±1.0	R	4.90	Yes
	Grant et al. (64)	30 M	28.8±8.1	Elite	Elite vs.	53.6±2.1	L		
				Novice	Recreational	45.4±2.1	L	3.86	Yes
					Elite vs.	54.2±2.3	R		
					Recreational	48.1±2.3	R	2.65	Yes
	Gurer et al. (67)	46 MF	18-50	1-4 CE	1-4 CE vs All	44.7±10.4	R	-0.05--0.30	No
		49 MF		5-10 CE	5-10 CE vs All	45.2±9.0	R	-0.29-0.05	No
		23 MF		11-15 CE	11-15 CE vs All	47.8±12.0	R	0.05-0.26	No
		21 MF		16-20 CE	16-20CE vs. All	47.2±7.8	R	-0.07-0.32	No
	Wall et al. (187)	6 F	30.3±3.5	Elite	5.11-5.12 YDS vs	0.66±0.07	R/BM		
		6 F	28.7±2.4	Subelite	5.10-5.11 YDS	0.58±0.06	R/BM	1.33	Yes
		6 F	28.0±5.5	Subelite	5.9-5.10 YDS	0.54±0.06	R/BM	2.00	Yes
					5.11-5.12 YDS vs	0.63±0.08	L/BM		
					5.10-5.11 YDS	0.56±0.07	L/BM	1.00	Yes
					5.9-5.10 YDS	0.52±0.04	L/BM	2.75	Yes
Combat Sports	Bonitch-Gongora et al. (15) (Judo)	26 M	15.0±0.7	Elite	Elite vs.	47.0±9.4	D	0.64	Yes
		19 M	14.8±0.6	Novice	Novice	42.3±7.2	D		
		21 F	14.8±0.6	Elite	Elite vs.	31.2±4.1	D	1.17	Yes
		7 F	14.6±0.5	Novice	Novice	23.5±6.5	D		
	Demirkan et al. (27) (Wrestling)	13 M	16.6±0.8	Elite I	Elite I vs	45.1±9.8	R		
		25 M	16.4±0.7	Elite II	Elite II	45.0±10.4	R	0.01	No
		88 M	16.4±0.6	Amateur	Amateur	44.5±8.9	R	0.07	No
	Demirkan et al. (27)	15 M	16.3±0.8	**LW:** Elite	Elite vs.	36.6±7.2	R	-0.12	No

	(Wrestling)	31 M	16.2±0.7	Amateur	Amateur	37.4±6.8	R		
				MW:					
		12 M	16.5±0.7	Elite	Elite vs.	47.2±5.6	R	0.40	No
		32 M	16.6±0.5	Amateur	Amateur	44.7±6.2	R		
				HW:					
		11 M	16.7±0.6	Elite	Elite vs.	54.1±8.2	R	0.17	No
		25 M	16.6±0.6	Amateur	Amateur	53.1±5.9	R		
	Demirkan et al. (28) (Wrestling)	11 M	19.3±1.0	Elite	Elite vs.	54±8.0	R	0.64	No
		37 M	18.8±1.0	Sub-elite	Sub-elite	49±8.0	R		
					Elite vs,	53±7.8	L	0.63	No
					Sub-elite	48±7.9	L		
	Drid et al. (33) (Judo)	5 M	25.6±3.6	Elite	Elite vs.	64.3±1.96	L	3.07	No
		5 M	25.8±4.1	Subelite	Subelite	58.2±1.99	L		
					Elite vs.	69.0±3.74	R	2.23	No
					Subelite	62.6±2.87	R		
	Garcia-Pallares et al. (56) (Wrestling)			**LW:**					
		6 F	18.2±0.8	Elite	Elite vs.	30.9±5.5	D	0.74	Yes
		12 F	16.8±1.1	Amateur	Amateur	26.9±5.4	D		
				MW:					
		7 F	18.7±1.5	Elite	Elite vs.	34.7±6.3	D	0.49	Yes
		10 F	16.9±1.3	Amateur	Amateur	32.9±3.7	D		
	Garcia-Pallares et al. (55) (Wrestling)			**LW:**					
		18 M	17.5±1.1	Elite	Elite vs.	45.0±6.5	D	0.66	Yes
		15 M	16.1±1.0	Amateur	Amateur	39.7±8.0	D		
				MW:					
		18 M	18.5±1.5	Elite	Elite vs.	53.1±7.8	D	0.83	Yes
		19 M	17.1±1.8	Amateur	Amateur	46.5±8.0	D		
				HW:					
		10 M	19.6±1.5	Elite	Elite vs.	55.6±8.9	D	0.37	No
		12 M	17.2±1.7	Amateur	Amateur	52.1±9.5	D		
	Nikooie et al. (122) (Wrestling)	5 M	25.6±1.9	Senior I	Medal vs.	0.59±0.04	D/BM		
		7 M	25.5±2.5	Senior II	No Medal	0.52±0.06	D/BM	1.17	Yes
		5 M	19.1±0.7	Junior I	Medal vs.	0.57±0.06	D/BM		
		9 M	18.8±0.5	Junior II	No Medal	0.49±0.05	D/BM	1.60	Yes
	Roemmich and Frappier (143) (Wrestling)	19 M	16.2±0.2	High school	Winners (84%)	53.2±2.4	R	3.33	Yes
						52.8±2.2	L	3.33	Yes
		19 M	16.1±0.2		Losers (64%)	47.2±1.8	R		
						45.8±2.1	L		
	Sanchez et al. (148) (Judo)	71 M	15-19	State	Gold vs	47.81±7.92	DND		
					-Silver	52.82±8.20	DND	-0.61	No
					-Bronze	48.31±6.29	DND	-0.08	No
					-No medal	47.32±6.00	DND	0.08	No
	Sanchez et al. (148) (Judo)	31 F	15-19	State	Gold vs	39.30±5.16	DND		
					-Silver	35.85±5.30	DND	0.65	No
					-Bronze	31.53±3.35	DND	2.32	Yes
					-No medal	30.91±2.66	DND	3.15	Yes
Field Hockey	Keogh et al. (87)	35 F	19.4±1.0	Regional	Regional vs	36±1	D	2.00	No
		39 F	20.3±1.5	Club	Club	34±1	D		
	Sharma et al. (157)	35 M	18-23	National	National vs	36.03±4.95	R		
		25 M	18-23	State	State	36.65±3.88	R	-0.16	No
					National vs	36.57±4.67	L		
					State	37.77±3.40	L	-0.35	No
Football (American)	Shields et al. (159)	167 M	21-29	NFL	Starters vs.	65.9±11.6	NA		
					-Rookies	63.6±7.1	NA	0.32	No
					-Nonstarters	61.4±9.5	NA	0.47	No
	Straub (168)	28 M	28.2±NA	NFL	NFL-offence vs.	58.59±4.66	DND		
		21 M	20.1±NA	College	College-offence	53.51±4.61	DND	1.10	Yes
		25 M		NFL	NFL-defence vs.	58.12±6.47	DND		
		19 M		College	College-defence	55.48±4.20	DND	0.63	No

Handball	Massuca et al. (109)	41 M	26.2±4.9	Elite	Elite vs.	7.21±5.99	DND	0.22	Yes
		126 M	25.2±4.8	Subelite	Subelite Div2/3	5.06±5.35	DND		
Horse Riders	Hobbs et al. (75) (Equestrian)	132 F	39±12	Leve 1-3	Level 1 vs	25.1±8.6	L	0.20	No
					Level 3	23.1±10.2	L		
					Level 1 vs	26.0±8.9	R	0.03	No
					Level 3	25.7±11.0	R		
Ice Hockey	Peterson et al.(129)	24 M	18-24	College	Division I vs.	66.8±8.4	D	1.17	Yes
		11 M	18-24	College	Division III	56.6±8.7	D		
	Zane, J. (202)	21 M	24.3±2.8	College	High velocity vs	44.6±5.5	D		
			25.2±5.9		Low velocity	39.4±5.2	D	1.00	Yes
		20 F	25.1±6.4	College	High velocity vs	30.5±6.3	D		
			22.1±3.7		Low velocity	22.8±2.2	D	3.50	Yes
Rowing	Secher (156)	7 M	26.0±0.6	National	Elite vs.	76.0±4.9	D	3.33	Yes
		11 M	24.2±0.7	Club	Subelite	67.0±2.7			
Strength Events	Fry et al. (52)	20 M	14.8±2.3	Weightlifters	Elite vs.	52.5±8.1	D	0.93	Na
		95 M			Non-elite	42.2±11.1	D		
Tennis	Knudson (89)	6 M	27±5		Advanced vs.	56.1±6.5	ND	-0.11	No
		6 M	40±9		Intermediate	56.8±4.9	ND		
					Advanced vs.	43.6±5.4	BHG	0.77	No
					Intermediate	39.4±6.8	BHG		
	Ulbricht et al. (183)	24 M	11.5±0.3	National	U12 National vs	24.2±3.4	D	0.68	Yes
		102 M	11.3±0.4	Region	U12 Regional	21.6±3.8	D		
		26 M	13.1±0.5	National	U14 National vs	28.6±5.6	D	0.06	No
		229 M	12.9±0.5	Region	U14 Regional	28.3±6.2	D		
		28 M	15.0±0.5	National	U16 National vs	43.0±7.3	D	0.37	No
		137 M	14.9±0.5	Region	U16 Regional	37.7±8.9	D		
		17 F	11.5±0.3	National	U12 National vs	23.2±4.1	D	0.64	Yes
		65 F	11.4±0.3	Region	U12 Regional	20.6±4.1	D		
		28 F	12.9±0.5	National	U14 National vs	29.0±5.5	D	0.30	No
		149 F	12.9±0.5	Region	U14 Regional	27.4±5.2	D		
		24 F	14.9±0.5	National	U16 National vs	35.3±4.4	D	0.76	Yes
		73 F	14.8±0.5	Region	U16 Regional	32.1±4.0	D		
Volleyball	Pion et al. (132)	13 F	15.4±1.6	Elite	Elite vs.	36.7±4.9	D	0.21	No
		8 F	15.1±1.4	Subelite	Subelite	35.3±6.7	D		

A = single A minor league baseball; AA = double A minor league baseball; AAA = triple A minor leagure baseball; BHG = backhand tennis stroke grip position; BM = body mass in kg; CE = climbing experience in year; D = dominant hand; DND = mean handgrip strength of the dominant and non-dominant hands; ES = effect size; F = female subjects; HGS = handgrip strength; HW = heavy weight class; L = left hand; LEN = average ratio of 3 personal best times to the world record; LW = lightweight class; M = male subjects; MLB = major league baseball; MW = middleweight class; NA = information not available; ND = non-dominant hand; NFL = national football leauge; p = level of significance; R = right hand; U12 = athlete under 12 years of age; U14 = athletes under 14 years of age; U16 = athletes under 16 years of age; UIAA = Union Internationale des Associations d’Alpinisme (climbing ranking system); YDS = Yosemite decimal system (climbing rankings system).

Table 4. Relationship between sport performance measures and handgrip strength

Sport	Reference	n-sex	Age (yrs)	Level	Performance measure	Output	HGS (kgf)	Hand	*r*	*p*≤0.05
Baseball and Softball	Albert et al. (3)	19 F	19.2±1.0	College	BBV (mph)	NA	NA	Na	0.41	Yes
	Bonnette et al. (16)	23 M	20.6±1.3	College	Bat speed (mph)	85.2±5.6	60.7±8.0	NA	0.52	NA
					BBV (mph)	83.6±6.6			0.50	
	Fry et al. (51)	31 M	NA	College	Bat velocity (m/s)	37.4±3.0	49.0±8.6	R	0.37	No
					Slugging %	NA	46.3±9.0	L	0.59	Yes
					Batting average	NA			0.46	No
	Heitman et al. (73)	40 F	21.3±3.7	College	Pitch speed (km/h)	48.1±6.0	36.5±4.8	D	0.22	No
	Hoffman et al. (76)	343 M	21-29	Pro	Home runs	NA	103-116	NA	0.32	Yes
					Total bases	NA			0.21	Yes
					Slugging %	NA			0.27	Yes
	Hughes et al. (78)	23 M	19.7±1.3	College	Bat speed (mph)	82.0±5.1	57.0±6.7	NA	0.32	No
	Mangine et al. (106)	47 M	27.8±3.4	Pro (MLB)	Fielding %	98.2±1.2	126±26	R+L	-0.09	No
	Nakata et al. (120)	164 M	6.4-15.7	Youth	Pitching (J)	26-55	14.3-32.1	L	0.89	Yes
							14.8-32.9	R	0.91	Yes
					Batting (J)	32-63		L	0.88	Yes
								R	0.90	Yes
					10m Sprint (s)	2.17-2.49		L	0.67	Yes
								R	0.68	Yes
					HJ (m)	1.53-2.06		L	0.82	Yes
								R	0.84	Yes
	Pugh et al. (134)	16 F	19.1±2.9	College	Pitch speed (km/h)	76.7±7.4	36.6±4.1	D	0.62	Yes
	Reed et al. (138)	47 M/F	21.5±2.0	College Students	Bat speed	NA	NA	ND	0.79	Yes
								D	0.79	Yes
					BBV	NA		ND	0.83	Yes
								D	0.85	Yes
	Spaniol et al. (165)	556 M	15.6±1.2	Youth	Bat speed (mph)	70.3±7.1	39.3±7.9	R	0.61	Yes
							39.2±8.3	L	0.61	Yes
								L+R	0.63	Yes
	Spaniol et al. (164)	34 M	20.6±1.3	College	Bat speed (mph)	87.4±6.0	61.4±8.9	Na	0.59	Yes
					BBV (mph)	78.2±4.2			0.83	Yes
	Szymanski et al. (172)	22 M	20.0±1.5	College	Bat speed (mph)	NA	NA	D	0.61	Yes
								ND	0.59	Yes
	Szymanski et al. (176)	30 M	Na	High School	Bat speed	NA	NA	ND	0.61	Yes
								D	0.56	Yes
					BBV	NA		ND	0.47	Yes
								D	0.42	Yes

	Weimer et al. (192)	10 M	20.8±1.0	College	Bat speed (m/s)	26.0±2.8	50.2±7.8 52.7±8.8	L R	-0.12 -0.06	No No
		14 F	19.5±1.1	College	Bat speed (m/s)	18.5±2.5	31.4±7.8 36.3±7.1	L R	0.38 0.70	No Yes
Basketball	Lupo et el. (104)	10 M	22.2±4.1	Subelite	Free throw	NA	NA	D	0.76	Yes
	McGill et al. (113)	14 M	20.4±1.6	College	Points/game	NA	52±9 50±7	R L	-0.39 -0.03	No No
					Assists/game	NA		R L	-0.14 -0.49	No No
					Rebounds/game	NA		R L	-0.55 0.09	Yes No
					Steals/game	NA		R L	-0.61 0.10	Yes No
					Blocks/game	NA		R L	-0.26 0.18	No No
Bowling	Tan et al. (179)	26 M 13 F	34.3±8.2	Elite	Bowling score	NA	38.1±8.8	D D	0.07 -0.12	No No
Climbing	Balas et al. (9)	136 M	24.7±na	Novice-Elite	Redpoint scale Finger hang (s) Bent-arm hang (s)	3-12 13-79 30-85	42-59	DND	0.55 0.53 0.49	NA
		69 F	26.0±na	Novice-Elite	Redpoint scale Finger hang (s) Bentarm hang (s)	3-12 7-71 14-69	27-44	DND	0.75 0.65 0.72	NA
	Gajewski et al. (53)	21 M	22.0±3.4		Climbing ability	23.0±4.9	8.4±1.2 N/kg	DND	0.56	Yes
	Mermier et al. (115)	24 M 20 F	30.4±6.0 32.2±9.2	5.6-5.13c YDS	Climbing score Flexibility Climbing time Laps completed		47.3 ±10.2 29.4±6.0	D D	0.80 0.04 -0.70 -0.70	Yes No Yes Yes
	Mitchell et al. (116)	10 M 10 F	20.7±3.0 23.2±3.8	5.10b YDS	Climbing time (s)	NA	NA	NA	-0.96 -0.88	Yes Yes
	Wall et al. (187)	18 F	28-30.3	Novice Expert	Bouldering	26.1-48.9	30.5-36.3 29.4-36.6	R L	0.67 0.63	Yes Yes
					Routing	7.4-37.1	0.54-0.66 0.52-0.63	R/BM L/BM	0.50 0.43	Yes Yes
					Outdoor	10.3-11.8		R L	0.64 0.59	Yes Yes
					Indoor	10.4-11.6		R L	0.50 0.50	Yes Yes
					Redpoint	10.5-12.2		R L	0.60 0.49	Yes Yes
	Watts et al. (191)	11 MF	28.7±4.5	5.12a YDS	Climbing time (s)	12.9±8.5 min	NA	DND	0.70	Yes
					Number of laps	2.8±2.2	NA	DND	0.70	Yes
Combat sports	Guidetti et al. (66)	8 M	22.3±1.5	Boxing Amateur	Ranking	NA	58.2±6.9	D	0.87	Yes
	Franchini et al. (49)	13 M	NA	Judo National	Wingate power Wingate work Throws-30s (#) Attacks (#)	8.13±0.75 349±47 11±1 15±5	54.3±8.3 53.2±7.4	R L	Na Na Na Na	No No No No
	Nikooie et al. (122)	12 M 14 M	23.0-28.0 18.3-19.8	Senior Junior	Performance (pooled data)	Medal vs. No Medal	51.3±3.7 46.1±3.1	D D	0.41	Yes
Cricket	Amritashish and Shiny (6)	15 M	20.7±1.8	Academy	Spin-off score	NA	44.9±4.6	D	0.03	No
	Sathya, et al. (149)	75 m	17-19	College	2 kg D medicine ball putt (m)	12.35±1.9	34.6±6.5 33.4±5.6	D ND	0.65	Yes
Equestrian	Keeton (85)	56 F	19.8	College	Points	NA	28.8	R	0.21	No

							27.2	L	0.09	No
Field Hockey	Sharma et al. (157)	35 M	18-23	National	VO$_2$ max	45.2±2.2	36.0±5.0	R	0.16	No
							36.6±4.7	L	0.19	No
					Slalom sprint (s)	17.5±1.6		R	0.01	No
								L	0.06	No
					Dribble test (s)	18.3±1.6		R	0.01	No
								L	0.08	No
		25 M	18-23	State	VO$_2$ max	44.4±2.0	36.7±3.9	R	0.02	No
							37.8±3.4	L	-0.00	No
					Slalom sprint (s)	17.5±2.0		R	-0.01	No
								L	0.09	No
					Dribble test (s)	18.4±1.8		R	-0.10	No
								L	-0.01	No
	Verma (184)	30 M	NA	National	Drag flick ability	NA	NA	NA	0.45	Yes
	Wassmer and Mookerjee (189)	37 F	20.2±1.5	College	Hitting power (s)	7.70±1.75	33.9±5.7	R	0.04	No
								L	0.13	No
					Hitting accuracy	22.1±6.3		R	-0.09	No
								L	-0.11	No
					Pushing power (s)	9.41±1.06		R	-0.12	No
								L	-0.10	No
					Pushing accuracy	16.6±7.0		R	-0.13	No
								L	-0.05	No
Football (American)	Agbuga, et al. (2)	41 M	20.6±2.1	College	Bench Press 1RM	124±24	57.2±8.9	D	0.25	No
	Straub (168)	40 M	20.1±NA	College	*Player Ranking*:	NA				
					Wide receiver		54.5-56.6	D	-0.20	NA
							52.5-54.3	ND	-0.10	
					Defensive end			D	-0.25	
								ND	-0.30	
					Defensive tackle			D	-0.70	
								ND	-0.10	
					Secondary			D	-0.40	
								ND	-0.60	
					Offensive tackle			D	0.60	
								ND	0.00	
					Guard			D	-0.50	
								ND	-0.50	
					Offensive back			D	0.03	
								ND	-0.26	
	Straub (168)	53 M	28.2±NA	Elite (NFL)	*Player Ranking*:	NA				
					Wide receiver		60.0-61.7	D	-0.30	NA
							55.5-56.1	ND	0.00	
					Defensive end			D	-0.60	
								ND	0.00	
					Defensive tackle			D	0.40	
								ND	-0.60	
					Linebacker			D	0.15	
								ND	-0.04	
					Secondary			D	-0.04	
								ND	0.27	
					Offensive tackle			D	0.12	
								ND	0.12	
					Guard			D	0.43	
								ND	0.34	
					Offensive back			D	-0.21	
								ND	0.26	
Football (Soccer)	James et al. (80)	60 M	13.8±1.3	Club	5 m sprint (s)	NA	NA	DND	-0.73	Yes
					T-Test (s)			DND	-0.40	Yes

Golf	Brown et al. (18)	16 F	24.8±7.3	Elite	Club speed (m/s)	39.5±2.5	32.9±5.3	L	0.54	Yes
							33.3±5.9	R	NA	No
	Hellstrom (74)	30 M	18-30	Elite	Club speed (m/s)	49.8±2.7	52.2±8.7	L	0.31	No
							55.0±7.7	R	0.36	Yes
	Wells et al. (193)	15 M 9 F	22.7±5.1	Elite	Driver ball speed (km/h)	245±28	46.2±11.9	D	0.78	Yes
							45.8±12.2	ND	0.82	Yes
					Driver distance (m)	224±31		D	0.77	Yes
								ND	0.81	Yes
					5 Iron ball speed (km/h)	198±18		D	0.78	Yes
								ND	0.85	Yes
					5 Iron distance (m)	166±18		D	0.78	Yes
								ND	0.85	Yes
					Score (shots/round)	73.2±2.4		D	-0.68	Yes
								ND	-0.71	Yes
					Greens in regulation	12±1.5		D	0.31	No
								ND	0.21	No
					Putt distance after chip (feet)	8.4±1.7		D	-0.23	No
								ND	-0.36	No
					Putts per round	30.8±1.8		D	-0.31	No
								ND	-0.44	Yes
Gymnastics	Ruprai et al. (146)	25 M	22.0±2.0	NA	HGS endurance (s)	32.3±6.9	61.1±7.2	D	0.82	Yes
Handball	Phulkar (131)	NA	18-22	Institute	Handball ability	NA	NA	R	0.78	Yes
					Handball ability			L	0.68	Yes
	Tsakalou et al. (182)	16 M	12.6	Club	Ball speed (km/h)	60.8	29.0	D	0.59	Yes
		17 F	12.5		Ball speed (km/h)	55.8	25.4	D	0.59	
		58 M	13.5		Ball speed (km/h)	67.8	39.8	D	0.70	Yes
		30 F	13.5		Ball speed (km/h)	55.8	27.4	D	0.70	
	Zapartidis et al. (203)	75 M	13.4±0.4	Club	Ball speed (km/h)	67.5±7.3	39.8±8.1	D	0.68	Yes
		44 F			Ball speed (km/h)	56.5±5.1	30.7±0.1	D	0.68	
Ice Hockey	Alexander et al. (4)	30 M	NA	Elite	Slap shot speed	120-140	NA	D	0.25	No
					Wrist shot speed	112-127	NA	D	0.10	No
					Slap-shot accur.	19-23/30		D	0.16	No
					Wrist-shot accur.	18-21/30		D	0.09	No
	Zane, J. (202)	21 M	24.3±2.8	College	Slap shot (km/h)	106.6±4.8	44.6±5.5	D	0.49	Yes
					Wrist shot (km/h)	85.9±5.9		D	0.51	Yes
		20 F	25.1±6.4	College	Slap shot (km/h)	78.9±8.0	30.5±6.3	D	0.75	Yes
					Wrist shot (km/h)	63.0±6.1		D	0.69	Yes
Lacrosse	Marsh et al. (107)	15 F	20.3±1.7	College	Shot accuracy (cm)	15.2±4.3	34.5±5.6	D	0.19	No
					Shot velocity (m/s)	17.1±5.4		D	0.13	No
					Balance	1.56-10.59		D	<0.25	No
Mountain Bike	Chidley et al. (22)	43 na	25±5	Novice to Elite	Ride time (s)	214±34	41.6±8.1	DND	0.87	Yes
Paddle Sports	Hamano et al. (68)	11 M	20.6±0.9	Canoe	Ergometer power	183±48	50.0±11.5	D	0.75	Yes
		12 M	19.7±1.2	Kayak	Ergometer power	347±55	50.6±7.9	D	0.64	Yes
	Secher (156)	40 M	24-26	Row National	Rowing strength (Kp)	162-204	67-76	NA NA	0.43	Yes
Rugby	Tong and Wood (180)	30 M	NA	College	Bench press 1RM	100-114	60.4-67.5	R	0.46	Yes
							58.1-63.7	L	0.57	Yes
					Bench pull 1RM	87-98		R	0.57	Yes
								L	0.55	Yes
					Arm curl 1RM	54-61		R	0.54	Yes
								L	0.58	Yes

Swimming	Blanksby et al. (12)	82 MF	9-13	State	100 m freestyle (ratio to record)	NA	NA	NA	-0.36	No
					100 Butterfly (ratio to record)	NA	NA	NA	-0.38	No
	Douda et al. (32)	30 MF	10.5±0.5	Pre-pub.	50 m freestyle (s)	NA	8.9±3.4	R	-0.41	Yes
		42 MF	13.7±1.5	Pubertal	50 m freestyle (s)	NA	16.3±7.8	R	-0.54	Yes
		72 MF	10.5-13.7	Pooled	50 m freestyle (s)	NA	NA	R	-0.60	Yes
	Garrido et al. (57)	10 F	12.5±0.5	Pubertal	100 m freestyle	NA	32.8±5.5	D	0.82	Yes
					200 m freestyle				0.65	Yes
		14 F	14.6±0.5	Teens	100 m freestyle	NA	30.9±4.3	D	0.62	Yes
					200 m freestyle				0.21	No
		15 F	18.6±2.3	Senior	100 m freestyle	NA	33.5±5.9	D	0.54	Yes
					200 m freestyle				0.59	Yes
		11 M	15.0±0.5	Teens I	100 m freestyle	NA	46.6±9.7	D	0.63	Yes
					200 m freestyle				-0.01	No
		10 M	16.4±0.5	Teens II	100 m freestyle	NA	48.1±7.7	D	0.49	No
					200 m freestyle				-0.18	No
		18 M	21.8±2.3	Senior	100 m freestyle	NA	52.0±5.9	D	0.31	No
					200 m freestyle				0.26	No
	Geladas et al. (58)	178 M	12-14	Youth	100m freestyle (s)	65.5±0.25	34.0±0.6	DND	-0.73	Yes
		85 F			100m freestyle (s)	68.1±0.22	28.2±0.6	DND	-0.18	No
	Saavedra et al. (147)	66 M	13.6±0.6	National	LEN 800 m	508±71	28.7±6.8	NA	0.51	NA
		67 F	11.5±0.6		LEN (100-800m)	476±76	15.9±4.2	NA	0.54	NA
	Zampagni et al. (200)	135 M/F	40-80	Elite	50m freestyle	34.4±5.8	36-44	D	-0.72	Yes
					100m freestyle	69.8±9.1			-0.57	Yes
					200m freestyle	164±28			-0.58	Yes
					400m freestyle	359±90			-0.57	Yes
					800m freestyle	716±109			-0.39	Yes
Strength Events	Fry et al. (52)	20 M	14.8±2.3	Elite	1RM Snatch	95.6±14.8	52.5±8.1	D	0.38	NA
					1RM Clean&Jerk	125±20				
		95 M		Subelite	1RM Snatch	62.1±23.9	42.2±11.1	D		
					1RM Clean&Jerk	82±31				
	Schoffstall et al. (153)	4 M	25±9	State	1RM squat	200±30	63.0±10.0	R	0.97	Yes
					1RM bench press	119±21	64.2±8.7	L	0.98	Yes
					1RM deadlift	212±51			0.97	Yes
		3 F	33±13		1RM squat	41±6	33.8±6.9	R	0.97	Yes
					1RM bench press	50±9	37.0±3.7	L	0.98	Yes
					1RM deadlift	88±13			0.97	Yes
Tennis	Cohen et al. (24)	40 M	33.7±7.1	Elite	Serve speed	NA	NA	D	<0.30	No
	Girard & Miller (61)	12 M	13.6±1.4	Junior	Player ranking	Scale	17.6±6.4	D	-0.67	Yes
							14.5±4.8	ND	-0.29	No
					5m sprint (s)	1.19±0.07		D	-0.77	Yes
								ND	-0.67	Yes
					10m sprint (s)	2.02±0.14		D	-0.77	Yes
								ND	-0.67	Yes
					20m sprint (s)	3.55±0.27		D	-0.76	Yes
								ND	-0.55	Yes
					SJ (W/kg)	34.1±8.0		D	0.77	Yes
								ND	0.63	Yes
					CMJ (W/kg)	33.0±13.1		D	0.83	Yes
								ND	0.72	Yes
					DJ (W/kg)	22.1±4.3		D	0.59	No
								ND	0.41	No
	Pugh et al. (133)	15 M	20.8±2.0	College	Ball speed (km/h)	173.8±6.4	55.1±9.7	D	0.41	No

	Roetert et al. (144)	83 M	11.6±0.6	Junior	Ranking	NA	22.0±5.8	D	0.02	No
							18.4±5.1	ND	0.02	No
					Service	NA		D	0.32	No
					Forehand.	NA		D	0.18	No
					Backhand	NA		D	0.17	No
								ND	0.32	No
					Push up (reps)	26.5±9.0		D	0.25	Yes
								ND	0.19	No
					CMJ (m)	0.37±0.06		D	0.28	Yes
								ND	0.34	Yes
					Sit & reach (m)	0.58±0.52		D	0.15	No
								ND	0.19	No
					Response time (s)	0.37±0.06		D	0.26	Yes
								ND	0.21	No
	Smart et.a al. (161)	35 MF	25.2±7.0	College Subelite	Serve velocity (m/s)	NA	NA	D	0.66	Yes
	Ulbricht et al. (183)	902 MF	11-16	Junior	Ranking U12 Ranking U14 Ranking U16	NA	20.6-24.2 27.4-29.0 32.1-43.0	D D D	<0.24 <0.30 <0.39	No No No
Volleyball	Kilic and Binboga (88)	69 F 44 M	15-17	High School	Vertical jump (m)	0.45-0.58	29.0-43.4 (pooled)	R L	0.65 0.56	Yes Yes
					Leg strength (kg)	91-139	28.2-40.8 (pooled)	R L	0.67 0.61	Yes Yes
	Melrose et al. (114)	29 F	14.3±1.4	Club	Serve velocity (m/s)	16.1±2.5	34.5±5.5	D	0.60	NA
Water polo	Abraldes et al. (1)	30 M	NA	Elite	Throwing velocity (m/s)	NA	NA	D	0.36	Yes
	Ferragut et al.(40)	94 M	24.5±5.3	Elite:	**No goalkeep:**					
		20 M		-Centres	Throwing velocity	21.4±4.4	58.6±5.4	D	0.50	Yes
		45 M		-Wings	Throwing velocity	21.3±3.7	55.0±5.6	D	NA	No
					With goalkeep:					
				-Centres	Throwing velocity	20.8±4.6	58.6±5.4	D	NA	No
				-Wings	Throwing velocity	20.8±3.6	55.0±5.6	D	0.38	Yes
	Ferragut et al. (41)	19 M	24.0±5.1	National team	Throwing speed (km/h)	72.3±3.5	47.7±6.7	D	0.50	Yes
	Ferragut et al. (42)	13 M	26.1±4.8	Elite	Throwing velocity (m/s)	20.5±1.2	44.2±6.6	D	0.60	Yes
	Martinez et al. (108)	46 F	22.5±5.1	Elite	Throwing velocity (m/s)	14.8-17.3	25.3-37.4	D	NA	No

BBV = batted-ball velocity; BM = body mass in kg; CMJ = countermovment jump; D = dominant hand; DJ = drop jump; F = female subjects; FINA = swim times converted to FINA points in comparison to the world record; FEV = force expiratory volume; FIV = forced inspiratory volume; HGS = Handgrip strength; HJ = horizontal jump; HW = heavy weight class; L = left hand; LEN = average ratio of 3 personal best times to the world record; LW = light weight class; M = male subjects; MLB = major league baseball; MW = middle weight class; NA = information not available; ND = non-dominant hand; NFL = national football league; p = level of significance; R = right hand; r = Pearson product moment correlation; SJ = squat jump; U12 = athlete under 12 years of age; U14 = athletes under 14 years of age; U16 = athletes under 16 years of age; VO_2 max = maximum volume of oxygen comsumed; YDS = Yosemite decimal system (climbing rankings system).