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Bilateral Differences in Muscle Architecture and Increased Rate of Injury in National Basketball Association Players

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Context: Professional basketball players have demanding schedules that, in combination with certain underlying physical characteristics and side-to-side strength and power imbalances, may make them vulnerable to lower extremity injuries.

Objective: To examine the relationship among skeletal muscle architecture, lower body power, and games missed because of lower extremity injury (%MISS) in professional basketball players.

Design: Cross-sectional study.

Setting: Human Performance Laboratory.

Patients or Other Participants: Nine players under contract for Orlando Magic were assessed. We compared athletes who were injured (n = 4, height = 203.2 ± 5.5 cm, mass = 105 ± 7.5 kg, age = 25.0 ± 2.8 years) and those who remained healthy (n = 5, height = 200.2 ± 12.2 cm, mass = 100.1 ± 16.6 kg, age = 22.4 ± 1.9 years) during the season.

Main Outcome Measure(s): Bilateral ultrasonographic measurements of muscle thickness, pennation angle, echo intensity, and cross-sectional area of the rectus femoris and vastus lateralis were collected before regular-season play. Subsequently, muscle thickness and pennation angle were used to compute fascicle length. Along with unilateral jumping power, inferences were made upon the magnitude of the relationship between the percentage bilateral difference in these measures and %MISS, as well as between injured and healthy athletes.

Results: The data indicated likely relationships between %MISS and age ($r = 0.772$), and between %MISS and bilateral differences in rectus femoris cross-sectional area (7.8% ± 6.4%; $r = 0.657$) and vastus lateralis cross-sectional area (6.2% ± 4.8%; $r = 0.521$), as well as a possible relationship with vastus lateralis muscle thickness (7.9% ± 8.9%; $r = 0.444$). Echo-intensity differences in the vastus lateralis were greater in injured (8.0% ± 2.4%) versus healthy athletes (3.2% ± 2.0%). Although a 2-fold difference in mean jumping power was observed between injured (26.3 ± 14.9 W) and healthy athletes (13.6 ± 8.7 W), these differences were not statistically significant ($P = .20$).

Conclusions: In the present sample, lower extremity side-to-side differences may be related to an increased risk for lower extremity injury. Future researchers using larger sample sizes need to identify normal versus at-risk ranges for bilateral differences in muscle structure and power of the lower extremities of professional basketball players and athletes in other sports.

Key Words: sport science, bilateral deficits, jump power, muscle imbalances, elite athletes

Key Points

- Bilateral differences in the lower extremity may be related to an increased risk for injury.
- A 2-fold difference in power performance was noted between injured and healthy athletes, but this difference in a small sample of participants was not statistically significant.

Physiologically, a professional basketball game is quite demanding.[1] In one 48-minute game, a single player may travel a distance[1] greater than 6000 m via a variety of short, moderate- to high-intensity exertions[2] that include sprints and quick changes of direction as well as powerful jumps. Over the course of an entire National Basketball Association (NBA) season, a player may participate in 82 regular-season competitions (2–5 games per week), in addition to daily practice sessions and preseason and postseason practices and games. Although the total demand on a single player may vary as a result of a player's specific roles (eg, position responsibilities), playing time, travel schedule, and days off,[3] the ability to remain healthy during such a demanding schedule may depend on underlying physical factors that may make some athletes more susceptible to injury.

In the NBA, 60% of all game-related injuries (and 64.6% of all injuries) affect the lower extremity.[4] This equates to an injury rate of 11.6 lower extremity injuries per 1000 game appearances.[4] It has been reported that previous injury to the lower extremity,[5–7] bilateral lower limb imbalances,[8–11] and age[5] are all risk factors for lower extremity injury in anaerobic team sports. Authors of several studies of professional basketball players have examined injury-prediction models using bilateral measurements of skeletal structure,[12] connective tissue,[13] and isokinetic strength,[11] as well as drop-jump and 10-second jump performance.[11] However, there has been little to no examination of the effect of bilateral muscle architecture and muscle performance on injury risk. Recent technologic advances have provided a valid, reliable, noninvasive method to assess skeletal muscle architecture using ultrasound.[14,15] To date, we are unaware of any researchers who have examined bilateral differences in muscular architecture and power performance in NBA athletes, and only a few have explored bilateral performance differences in basketball players in general.

A certain degree of bilateral strength or power imbalance is apparent in elite basketball players,[11,16] which is likely related to the athlete's dependence on the dominant leg during cutting, pivoting, and jumping. However, what is deemed to be an acceptable degree of imbalance versus what may potentially lead to injury is not well understood. An imbalance that continues over the course of a season may become magnified, leading to a greater accumulation of fatigue, microtrauma, and eventually injury.[10,11] Considering the demanding stress on the lower extremities of an NBA player during a competitive basketball season, injury to the lower extremity may be related in part to bilateral abnormalities that were present at the start of the season. Given that specific skeletal muscle architectural properties have been associated with force, speed, and power production,[17–20] an investigation of their relationship with lower extremity injury may also prove to be beneficial. Therefore, the purpose of our study was to examine the relationships between bilateral differences in skeletal muscle architecture, measurements of power, and games missed because of injury in the lower extremities of NBA players.

METHODS

Study Design

Muscle architecture and power were assessed in basketball players from the Orlando Magic professional basketball organization during the week immediately before the beginning of the 2012–2013 regular season. Athletes' bilateral differences in both muscle architecture and power were compared with games missed because of lower extremity injury over the course of the regular season (82 games).

Participants

Nine players (height = 201.5 ± 9.4 cm, mass = 102.6 ± 13.0 kg, age = 23.5 ± 2.6 years) under contract to play for the NBA franchise Orlando Magic completed preseason testing. The number of games missed because of a lower extremity injury was examined as a percentage (%MISS) of the total number of games in the regular season (82 games). Information regarding the observed lower extremity injuries was provided by the team and included any bruise, sprain, strain, or tear to the Achilles tendon, ankle, calf, groin, hamstrings, hip, knee, or thigh. Subsequently, we calculated the mean percentage difference comparisons of all muscle architecture and power measures for players who missed at least 1 game because of lower extremity injury (INJ; n = 4, height = 203.2 ± 5.5 cm, mass = 105 ± 7.5 kg, age = 25.0 ± 2.8 years) and healthy (HLY; n = 5, height = 200.2 ± 12.2 cm, mass = 100.1 ± 16.6 kg, age = 22.4 ± 1.9 years) players. All performance assessments were part of the athletes' normal assessment routine. During the competitive season, all players participated in a regular weekly resistance-training program, completing 8 to 12 workouts per month. Players gave their informed consent as part of their sport requirements. This study was considered exempt in accordance with our institution's policies for use of human participants in research.

Measurements of Muscle Architecture

Noninvasive skeletal muscle ultrasound images were collected from the rectus femoris and vastus lateralis. Briefly, this technique uses sound waves at fixed frequencies to create in vivo, real-time images of the limb musculature. Participants reported to the Human Performance Laboratory and were instructed to lie supine for 15 minutes to allow fluid shifts to occur before images were collected.[21] A 12-MHz linear probe scanning head (model LOGIQ P5; General Electric, Wauwatosa, WI) was used to optimize spatial resolution and was coated with water-soluble transmission gel and positioned on the surface of the skin to provide acoustic contact without depressing the dermal layer. Measures of muscle cross-sectional area (CSA) and echo intensity (EI) were obtained using a sweep of the muscle in the extended field of view mode with gain set to 50 dB and image depth to 5 cm, and longitudinal images of muscle thickness (MT) and pennation angle (PNG) were taken using B-mode ultrasound.[22] All measures were taken in both the rectus femoris and vastus lateralis of both legs and performed by the same technician. After scanning, all images were analyzed offline using ImageJ (version 1.45s; National Institutes of Health, Bethesda, MD) image-analysis software. For these analyses, a known distance of 1 cm shown in the image was used to calibrate the software program.[23] Intraclass correlations (ICCs) for ultrasound measures were determined from 10 healthy adult participants in a previous investigation,[24] during which measurements were separated by at least 24 hours.

The anatomical location for all ultrasound measures was standardized for each muscle in all participants. For measures of the rectus femoris, the participant lay supine on an examination table, according to the instructions of the American Institute of Ultrasound in Medicine,[14] with the legs extended but relaxed and with a rolled towel beneath the popliteal fossa, allowing for a 10° bend in the knee as measured by a goniometer.[14] For measures of the vastus lateralis, the participant lay on his side with the legs together and relaxed, allowing for a 10° bend in the knee as measured by a goniometer. Cross-sectional area and EI were determined using the same images for the rectus femoris and vastus lateralis muscles. Measurements of the rectus femoris were taken in the sagittal plane, parallel to the long axis of the femur, and scanning occurred in the axial plane, perpendicular to the tissue interface at 50% of the distance between the anterior-inferior iliac to the proximal border of the patella. The vastus lateralis was measured at 50% of the distance from the most prominent point of the greater trochanter to the lateral condyle. Three consecutive images were analyzed and averaged using the polygon tracking tool in the ImageJ software to obtain as much lean muscle as possible without any surrounding bone or fascia for the CSA. The ICCs for rectus femoris and vastus lateralis CSA were 0.99 (SEM = 0.46 cm^2) and 0.99 (SEM = 1.26 cm^2), respectively. Concurrently, EI was determined by grayscale analysis using the standard histogram function in ImageJ.[22] The EI in the measure area was expressed as an arbitrary unit value between 0 and 255 (0 = black, 255 = white), with an increase in EI reflecting an increase in intramuscular connective tissue and adipose tissue relative to lean skeletal muscle. The ICCs were 0.91 (SEM = 3.47 arbitrary units) for the rectus femoris and 0.93 (SEM = 5.1 arbitrary units) for the vastus lateralis.

Measures of MT and PNG were taken at the same site described for CSA[25] but with the probe oriented longitudinal to the muscle–tissue interface for both the rectus femoris and the vastus lateralis. Within each muscle, MT was measured perpendicularly from the superficial aponeurosis to the deep aponeurosis. Three consecutive images were analyzed and averaged offline.[26] The ICCs for the rectus femoris and vastus lateralis MT were 0.96 (SEM = 0.11 cm) and 0.89 (SEM = 0.12 cm), respectively. Muscle-fiber PNG was determined as the intersection of the fascicles with the deep aponeurosis. The ICCs for rectus femoris and vastus lateralis PNG were 0.73 (SEM = 2.8°) and 0.86 (SEM = 1.44°), respectively. For both the rectus femoris and vastus lateralis, fascicle length across the deep and superficial aponeuroses was estimated using MT and PNG. Previously, this method of determining fascicle length had a reported estimated coefficient of variation of 4.7%.[20] Fascicle length can be found using the following equation[20]:

$$\text{Fascicle length} = \text{MT} \cdot \sin(\text{PNG})^{-1} \tag{1}$$

All unilateral measurements of muscular architecture are expressed as a percentage difference between legs.

Measurement of Vertical-Jump Power

Before physical exertion during preseason, body mass (±0.1 kg) and height (±0.1 cm) were measured using a Health-o-meter Professional Scale (model 500 KL; Pelstar, Alsip, IL). Subsequently, bilateral and unilateral vertical-jump power were determined from a Power Output Unit (Tendo Sports Machines, Trencin, Slovak Republic) that was attached at the waist of the player during the assessment. The Tendo unit consists of a transducer that measures *velocity* ($m \cdot s^{-1}$), defined as linear displacement over time. Subsequently, vertical-jump velocity was multiplied by the participant's body mass (kg) to calculate power (W). The jumping assessment began with 5 bilateral countermovement jumps, followed by 5 additional countermovement jumps from each leg, for a total of 15 jumps. The players were instructed to perform each jump with their hands placed upon their hips and were allowed to regain their balance between jumps (approximately 1–5 seconds). The average peak power and mean power of 5 (bilateral, right, and left) maximal jumps were used for statistical analysis. In basketball players, the ICCs for peak power and mean power, as measured by the Tendo unit, are 0.98 (SEM = 106.2 W) and 0.94 (SEM = 100.3 W), respectively (unpublished data, J. R. Hoffman, August 2014).

Statistical Analysis

We interpreted the relationship between %MISS and preseason measures of the percentage of bilateral difference in lower extremity muscular architecture and power during an NBA season by analyzing the magnitude of the relationships.[27,28] We used SPSS (version 20.0; SPSS Inc, Chicago, IL) to calculate Pearson product moment correlation coefficients and entered these with the sample size (n = 9) into the correlation coefficient statistic on a published spreadsheet[28] to determine the magnitude of the effect. The threshold value for positive or negative correlations was set at 0.1, which was previously reported to be the smallest clinically important correlation.[27] Inferences from correlations were determined as positive, trivial, or negative according to methods previously described[28] and were based on the confidence interval range relative to the smallest clinically meaningful effect. In the event of a positive or negative result, the correlation was reexamined at the 0.3 and 0.5 threshold values to determine if the small correlation was, in fact, a moderate or large correlation, respectively. To make inferences about the true effects of percentage bilateral differences among players, an analysis based on the magnitude of differences, calculated from 90% confidence intervals as previously described by Batterham and Hopkins,[28] was also performed. After relationship analysis, we compared INJ and HLY for mean percentage differences between the right and left lower extremities for all muscle architecture and power measures. These percentage difference scores were then analyzed via a published spreadsheet,[28] with the smallest nontrivial change set at 20% of the grand standard deviation.[28] All data are expressed as mean effect ± SD, with the percentage chances of a positive or negative outcome being evaluated by the following scale: <1%, *almost certainly not*; 1% to 5%, *very unlikely*; 5% to 25%, *unlikely*; 25% to 75%, *possible*; 75% to 95%, *likely*; 95% to 99%, *very likely*; and >99%, *almost certain*. If the *likely* range substantially overlaps both positive and negative values, the outcome is inferred as unclear.[29] Additionally, a Mann-Whitney ranked-sum test was used to examine the median differences between INJ and HLY. Published quantiles of the Mann-Whitney test statistic,[30] with a criterion α level of $P \leq .025$, were used to determine statistical significance.

RESULTS

All players began the regular season healthy. Over the course of the regular season, they missed 3.4 ± 5.7 games (4.2% ± 6.9% of the season) because of lower extremity injury. Analysis of the magnitude of correlation coefficient relationships between these variables and %MISS can be found in Table 1. The data revealed a strong positive correlation ($r = 0.772$; $P = .010$) between age and %MISS and a moderate positive relationship between %MISS and the percentage bilateral difference in rectus femoris CSA (7.8% ± 6.4%; $r = 0.657$; $P = .050$). Weak positive correlations were observed between %MISS and bilateral

Table 1. Relationship Between Bilateral Percentage Difference in Selected Variables and Percentage of Games Missed Because of Lower Extremity Injury (n = 9)

Variable	Threshold	r	P Value	r^2	% Positive	% Trivial	% Negative	Interpretation
Body mass, kg	0.1	0.044	.910	0.002	44.5	19.3	36.2	Unclear
Height, cm	0.1	0.049	.900	0.002	35.7	19.3	45.0	Unclear
Age, y	0.6	0.772	.010	0.596	79.2	20.8	0.0	Likely positive
Vertical-jump power								
Average, W	0.1	0.085	.830	0.007	48.5	19.0	32.5	Unclear
Peak, W	0.1	0.064	.870	0.004	46.5	19.2	34.4	Unclear
Lower extremity								
Leg length, cm	0.1	0.176	.650	0.031	57.5	17.7	24.8	Unclear
Rectus femoris								
Muscle thickness, cm	0.1	0.108	.780	0.012	50.8	18.8	30.5	Unclear
Pennation angle, °	0.1	0.093	.810	0.009	31.8	18.9	49.3	Unclear
Fascicle length, cm	0.1	0.106	.790	0.011	30.6	18.8	50.6	Unclear
Cross-sectional area, cm^2	0.4	0.657	.050	0.432	81.4	18.5	0.2	Likely positive
Echo intensity, au	0.1	0.031	.940	0.001	37.4	19.4	43.3	Unclear
Vastus lateralis								
Muscle thickness, cm	0.2	0.444	.230	0.197	74.9	20.3	4.8	Possibly positive
Pennation angle, °	0.1	0.085	.830	0.007	48.5	19.0	32.5	Unclear
Fascicle length, cm	0.1	0.138	.720	0.019	53.8	18.3	27.9	Unclear
Cross-sectional area, cm^2	0.2	0.521	.150	0.271	82.1	15.1	2.8	Likely positive
Echo intensity, au	0.1	0.180	.640	0.032	48.0	34.7	17.3	Unclear

Abbreviation: au, arbitrary unit.

percentage differences in vastus lateralis CSA (6.2% ± 4.8%; $r = 0.521$; $P = .150$), as well as a possible positive relationship with vastus lateralis MT (7.9% ± 8.9%; $r = 0.444$; $P = .230$). We found no relationships between %MISS and any of the measures of power. The means for all muscle architecture and power measures on each leg and the mean bilateral percentage difference within each variable are presented in Table 2.

Groupwise comparisons indicated a likely difference in vastus lateralis EI between INJ (8.0% ± 2.4%) and HLY (3.2% ± 2.0%) players, which was confirmed by the Mann-Whitney test statistic (U = 20; $P < .025$). No other significant group differences were observed. The mean percentage bilateral differences for all muscle architecture and power measures in both INJ and HLY players are shown in Table 3.

Table 2. Mean Differences in Lower Extremity Muscle Architecture and Power in Professional Male Basketball Players

Variable	Right Leg	Left Leg	Difference, %
Leg length, cm	53.3 ± 3.1	53.8 ± 3.1	1.21 ± 1.21
Vertical-jump power			
Average, W	833 ± 136	995 ± 109	19.5 ± 12.9
Peak, W	1801 ± 256	1930 ± 134	11.1 ± 11.1
Rectus femoris			
Muscle thickness, cm	2.94 ± 0.33	2.95 ± 0.42	6.2 ± 5.1
Pennation angle, °	11.8 ± 1.7	10.9 ± 1.3	8.4 ± 5.2
Fascicle length, cm	14.7 ± 2.7	15.8 ± 2.9	10.6 ± 6.8
Cross-sectional area, cm^2	17.5 ± 3.5	17.0 ± 3.5	7.8 ± 6.4
Echo intensity, au	53.4 ± 13.5	52.0 ± 10.9	7.9 ± 4
Vastus lateralis			
Muscle thickness, cm	2.26 ± 0.46	2.29 ± 0.42	7.9 ± 8.9
Pennation angle, °	14 ± 3.2	14.9 ± 4.3	15.5 ± 9.6
Fascicle length, cm	9.5 ± 1.9	9.4 ± 2.2	10.6 ± 8.4
Cross-sectional area, cm^2	33.6 ± 3.4	33.8 ± 3.9	6.2 ± 4.8
Echo intensity, au	62.1 ± 10.6	61.8 ± 11.5	5.4 ± 3.5

Abbreviation: au, arbitrary unit.

DISCUSSION

Age, bilateral differences in rectus femoris CSA, and EI and CSA imbalances in the vastus lateralis of professional basketball players were associated with injury rate in professional basketball players. These data provide support for existing evidence identifying age[5] and bilateral lower limb imbalances[8–11] as risk factors for lower extremity injury in athletes. These findings appear to be the first to illustrate architectural differences between the right and left lower extremity musculature in professional basketball players. Previously, Shambaugh and colleagues[10] observed a 4-fold greater difference in quadriceps girth, determined by tape measure, in recreational basketball players who would go on to suffer a lower extremity injury (0.93 ± 0.73 cm) during the season versus those who did not suffer an injury (0.26 ± 0.57 cm). This difference did not predict injury; however, limitations in the technology used to assess muscle girth may have limited its sensitivity. The measurement of thigh girth via tape measure does not differentiate among fat mass, lean mass, and skeletal, and connective tissue. Comparatively, we noted smaller (<10%) differences in bilateral muscle architecture in the present study, yet they were likely related to %MISS. Ultrasound measures of muscle structure may provide a greater degree of sensitivity to predict potential risk of injury.

The concern regarding bilateral imbalances may be related to the magnitude of the deficit, as well as the frequency with which it is exposed. Increased MT, CSA, and density (determined from EI in the present investigation) in skeletal muscle are associated with greater force and power production.[17,18,31] A bilateral imbalance may result in unequal forces produced in opposing limbs during either bilateral jumping or high-intensity running. In addition, unilateral jumps, which are frequently performed during a basketball game, may result in an athlete landing awkwardly on 1 leg. Considering the cumulative loads and physiologic demands over the course of a professional basketball season,[1–3] the

Table 3. Comparison of Bilateral Percentage Differences Between Injured and Healthy Professional Basketball Players

Variable	Injured Group (n = 4)	Healthy Group (n = 5)	*P* Value	Threshold	% Positive	% Trivial	% Negative	Mean Difference	Interpretation
Vertical-jump power									
Average, W	26.3 ± 14.9	13.6 ± 8.7	.200	2.59	85.1	8.3	6.6	13.0 ± 17.0	Unclear
Peak, W	15.8 ± 15.1	7.4 ± 5.5	.343	2.22	76.3	11.6	12.1	8.7 ± 16.0	Unclear
Lower extremity									
Leg length	1.6 ± 1.1	0.9 ± 1.3	.448	0.24	68.8	15.8	15.5	0.7 ± 1.6	Unclear
Rectus femoris									
Muscle thickness, cm	5.8 ± 4.9	6.8 ± 5.6	.740	1.02	52.4	20.2	27.5	1.2 ± 6.8	Unclear
Pennation angle, °	8.0 ± 6.4	8.8 ± 4.7	.825	1.03	48.6	19.6	31.8	0.9 ± 7.3	Unclear
Fascicle length, cm	9.3 ± 5.3	11.6 ± 8.0	.616	1.35	58.7	19.4	21.9	2.4 ± 8.6	Unclear
Cross-sectional area, cm^2	8.5 ± 9.5	7.4 ± 4.3	.840	1.28	48.4	18.6	33.0	1.1 ± 9.7	Unclear
Echo intensity, au	9.3 ± 3.9	6.8 ± 4.0	.404	0.79	71.6	14.6	13.9	2.4 ± 5.2	Unclear
Vastus lateralis									
Muscle thickness, cm	12.0 ± 10.1	4.4 ± 7.1	.251	1.78	81.5	10.1	8.3	7.6 ± 12.0	Unclear
Pennation angle, °	14.3 ± 10.4	16.2 ± 10.0	.772	1.92	50.8	20.2	29.0	2.1 ± 13.0	Unclear
Fascicle length, cm	7.8 ± 8.5	13.0 ± 8.3	.371	1.67	73.6	13.8	12.6	5.5 ± 11.0	Unclear
Cross-sectional area, cm^2	8.3 ± 5.0	4.8 ± 4.4	.348	0.97	75.1	13.2	11.8	3.3 ± 6.3	Unclear
Echo intensity, au	8.0 ± 3.6	3.2 ± 2.0	.062	0.69	94.9	3.2	1.9	4.5 ± 3.9	Likely positive

Abbreviation: au, arbitrary unit.

weaker limb may become more susceptible to injury,[10,11] especially in older players.[5] Significant relationships between lower extremity injury and bilateral imbalances in measurements of muscle function and jumping power have been demonstrated in basketball players.[9,11] Schiltz and colleagues[11] reported greater bilateral differences in drop-jump height (18.4% to 8.9%) and in 10-second jump height (20.5% to 5.5%) in professional basketball players with a history of lower extremity injury versus those without previous injury. Similarly, we observed a greater bilateral difference in mean power (26.3% ± 14.9% to 13.6% ± 8.7%) and peak power (15.8% ± 15.1% to 7.4% ± 5.5%) in INJ versus HLY, respectively; however, the magnitude of these power deficits was not significantly related to %MISS. Nevertheless, the relationships between muscle architecture imbalances (MT and CSA) and %MISS, as well as the differences in EI between INJ and HLY, which are associated with power,[17,18,31] warrant further investigation into their association with lower extremity power imbalances in a larger athletic population.

CONCLUSIONS

Our findings provide evidence that preseason bilateral muscle structural differences may be associated with games missed because of lower extremity injury in professional basketball players. The magnitude of these differences appears related to a greater percentage of games missed due to injury. In addition, bilateral differences in muscle power performance appear to be greater in athletes who were injured than in athletes who remained healthy during the season. Future authors, using larger sample sizes, need to identify normal versus at-risk ranges for bilateral differences in muscle structure and power of the lower extremities of professional basketball players and athletes of other sports.

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