Supplementary Material 2

Running Analysis & Return-to-Sport Assessment
(EMG, Isokinetic and Functional Performance Testing)

Scope of Analysis:

- EMG-based muscle activation analysis (ventral, dorsal, sagittal)
- Plantar pressure distribution & COP analysis
- Isokinetic strength testing
- Functional performance tests (Y-Balance, hop tests, jump analysis)

Evaluation:

Following each respective test result, an interpretation is provided in the context of sports medicine and functional performance.

Objective:

Assessment of neuromuscular control, strength symmetry, and functional capacity with regard to return-to-sport (RTS).

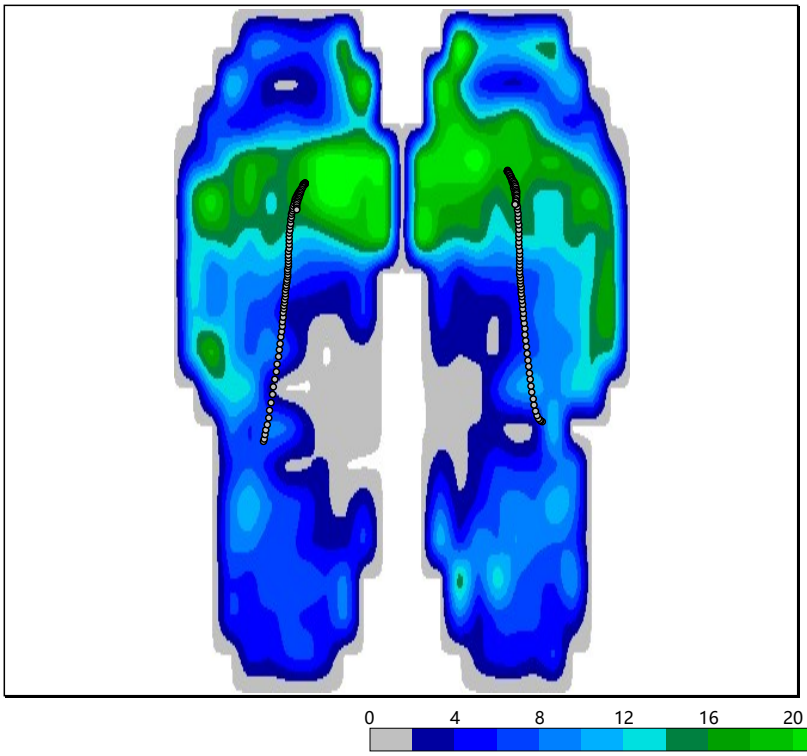
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1. EMG-based muscle activation analysis and plantar pressure distribution & COP analysis

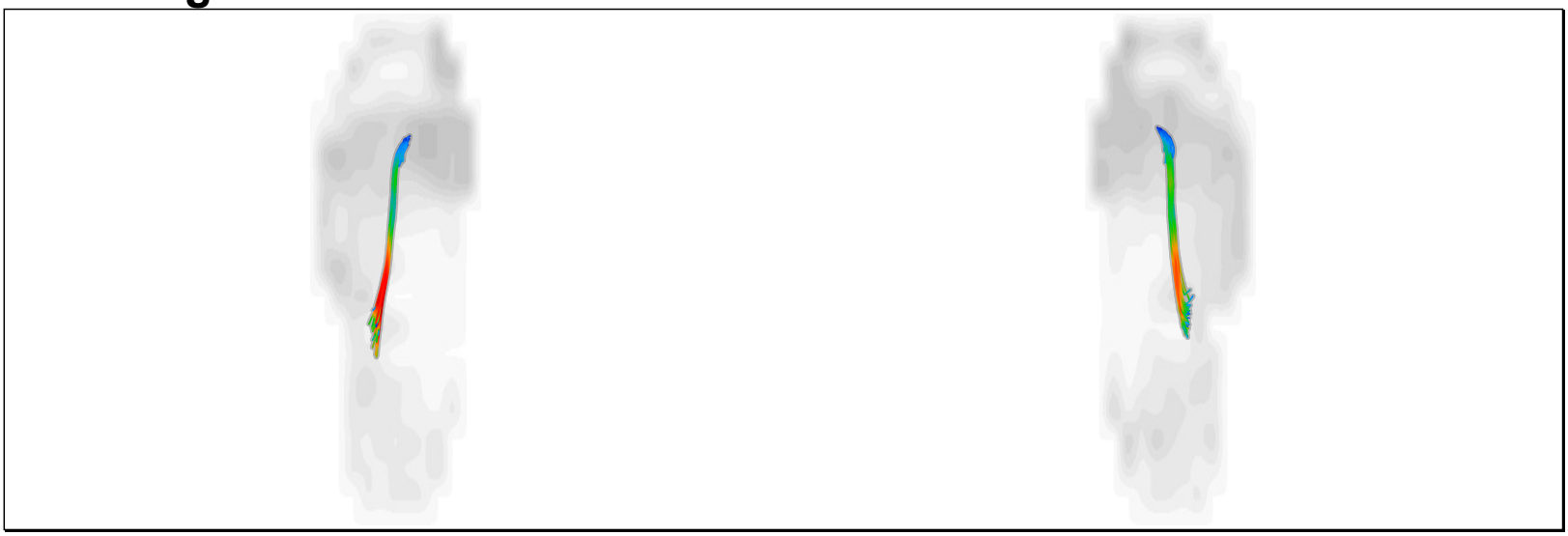
Druckverteilung

Mittelwert

VENTRAL



COP Diagram



Messkommentar Druck



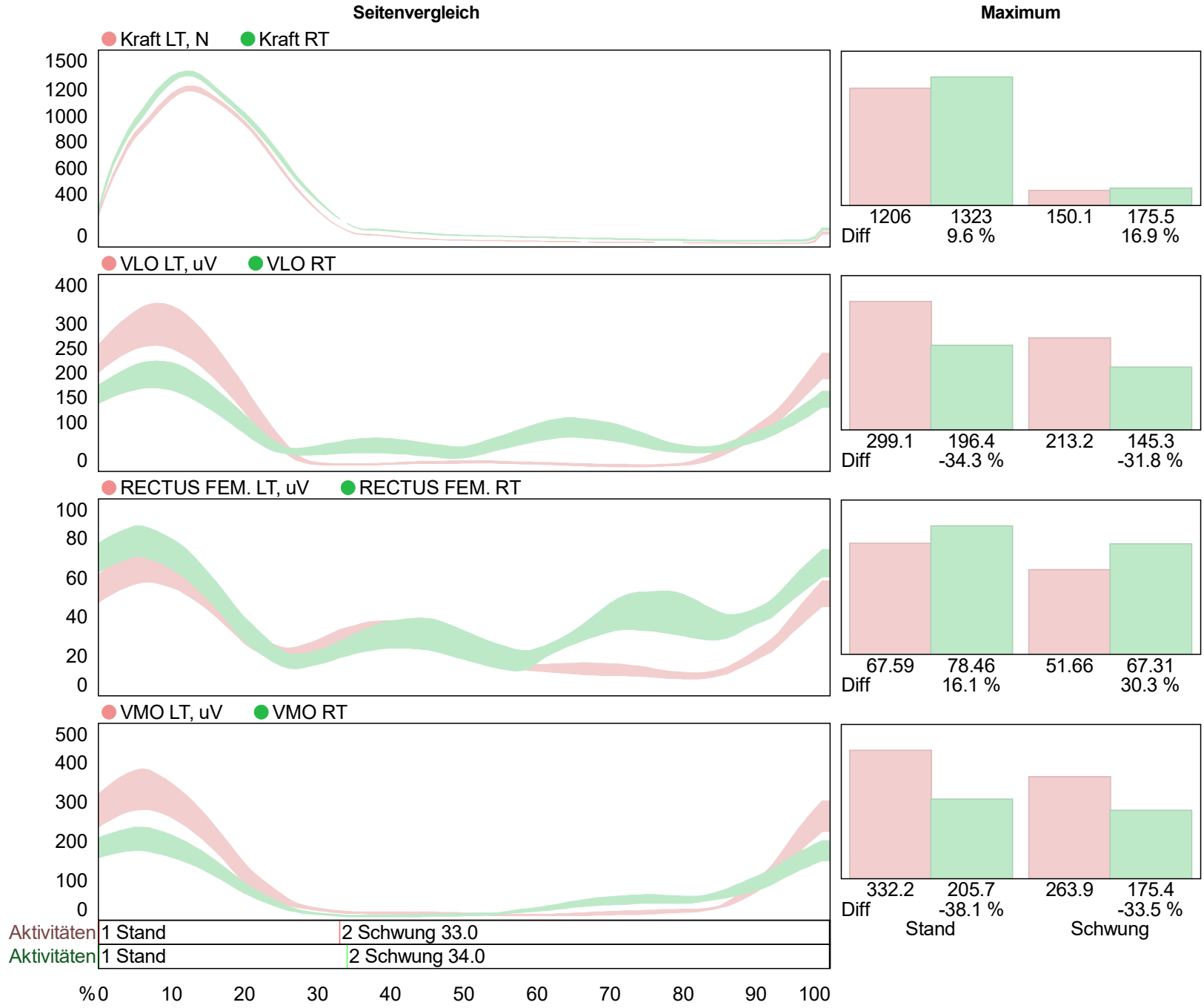
Laufphasen Parameter

Standphase, %	Links	32.7±0.8
	Rechts	34.1±0.5
	Diff, %	4.1
Einbeinstandphase, %	Links	32.7±0.8
	Rechts	34.1±0.5
	Diff, %	4.1
Schwungphase, %	Links	67.3±0.8
	Rechts	65.9±0.5
	Diff, %	-2.0

Zeitliche Parameter

Schrittzeit, ms	Links	373±4
	Rechts	364±3
	Diff, %	-2.6
Zeit Doppelschritt, ms		737±5
Kadenz, Schritte/min		163±1

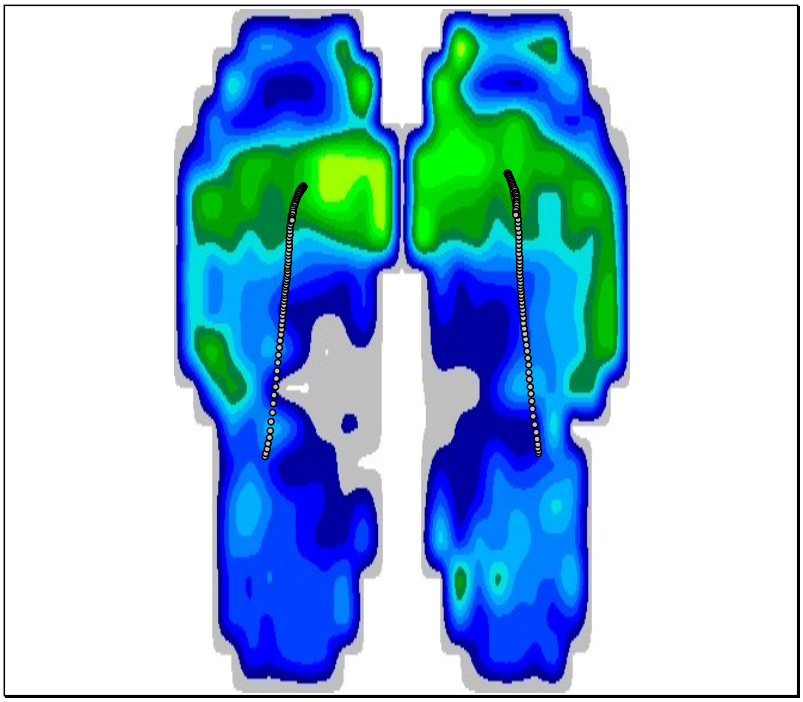
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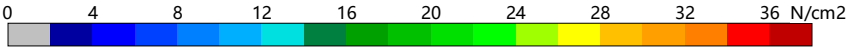


Messkommentar EMG

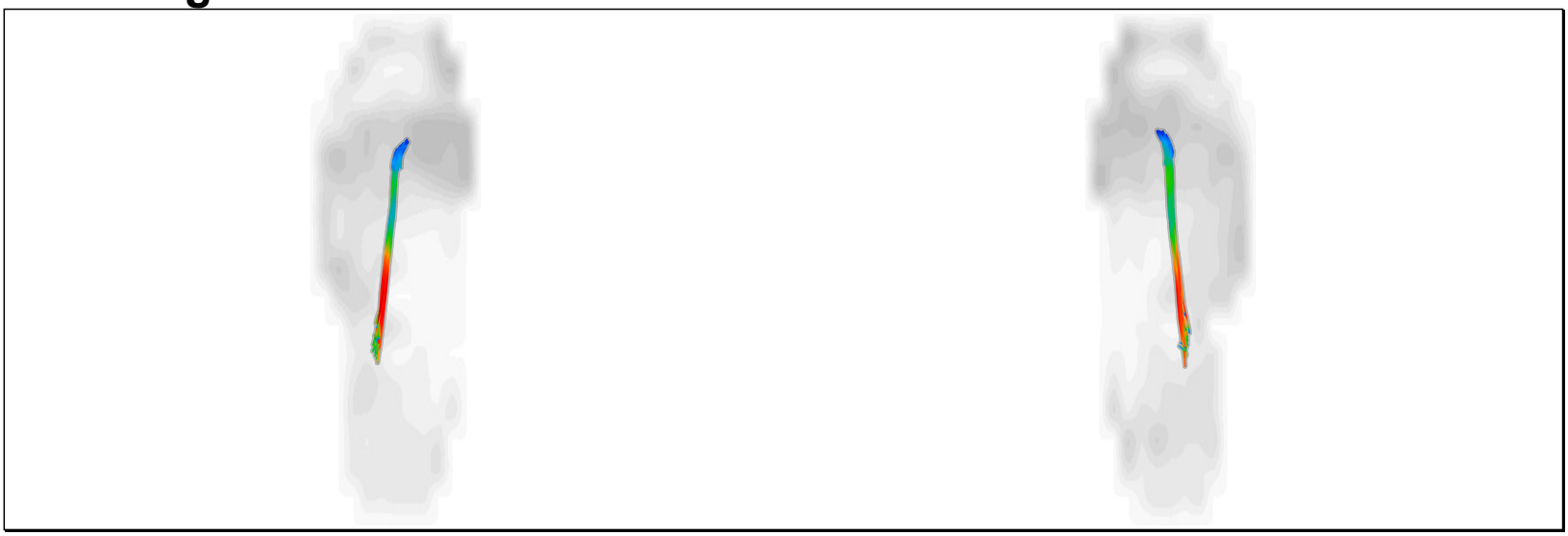
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Mittelwert





COP Diagram



Messkommentar Druck



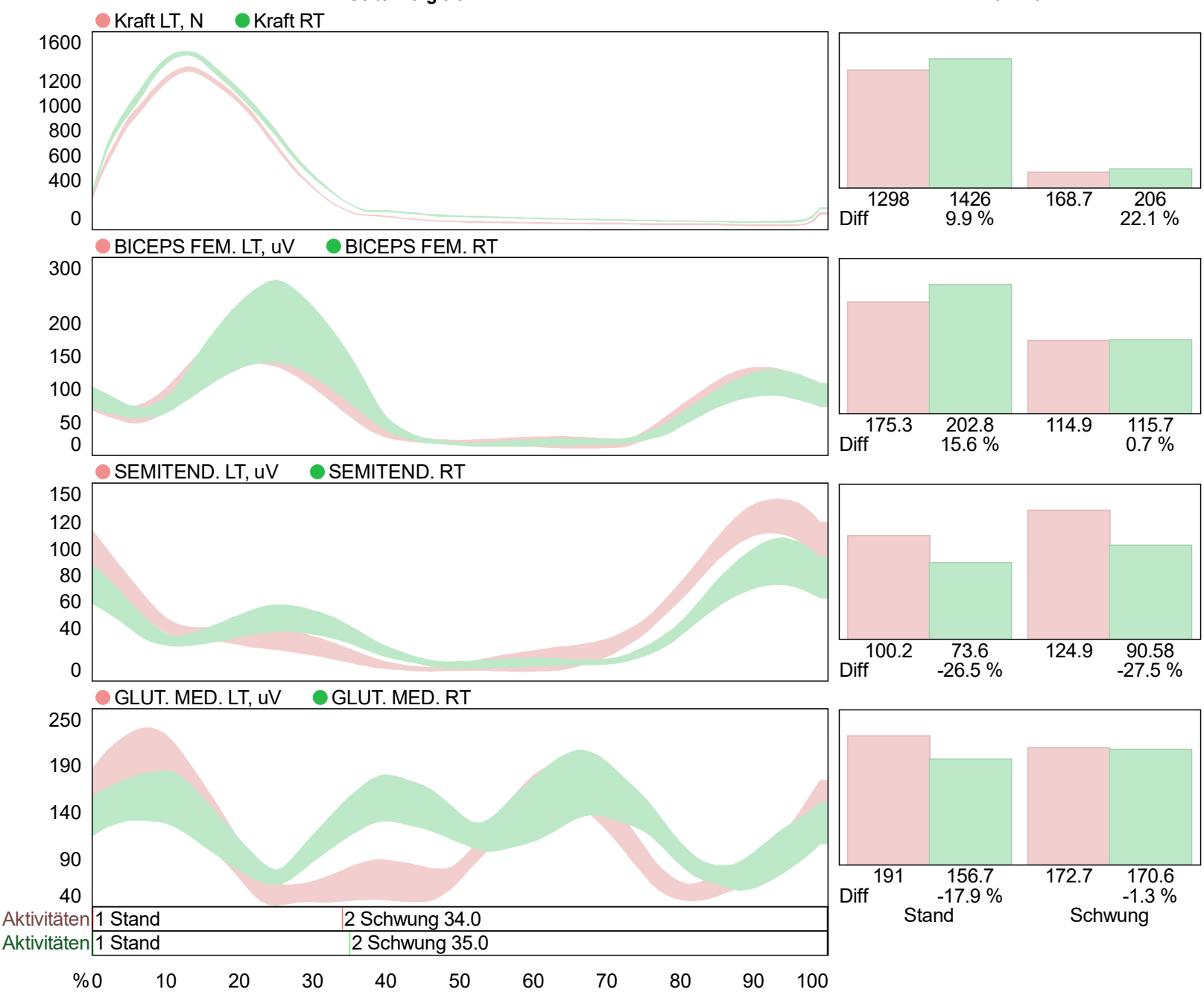
Laufphasen Parameter

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	Diff, %	1.3
Einbeinstandphase, %	Links	34.3±0.5
	Rechts	34.7±0.4
	Diff, %	1.3
Schwungphase, %	Links	65.7±0.5
	Rechts	65.3±0.4
	Diff, %	-0.7

Zeitliche Parameter

Schrittzeit, ms	Links	373±4
	Rechts	366±4
	Diff, %	-2.0
Zeit Doppelschritt, ms		739±5
Kadenz, Schritte/min		162±1

[redacted]



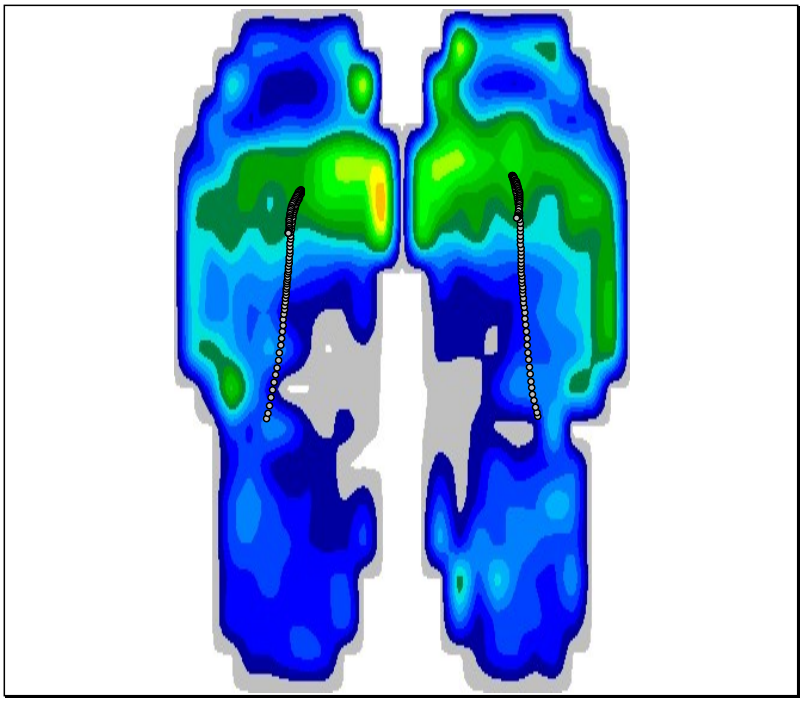
Messkommentar EMG

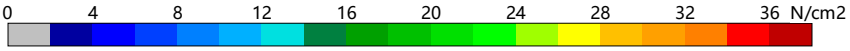
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Druckverteilung

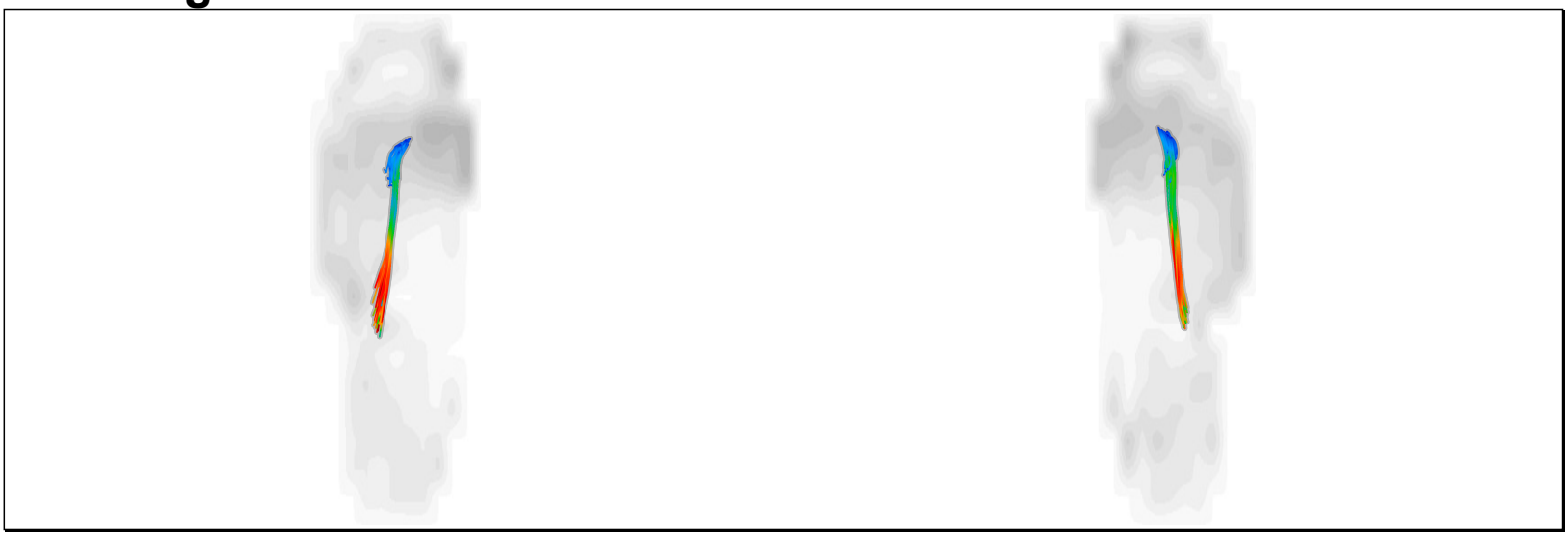
Mittelwert

SAGITTAL





COP Diagram



Messkommentar Druck

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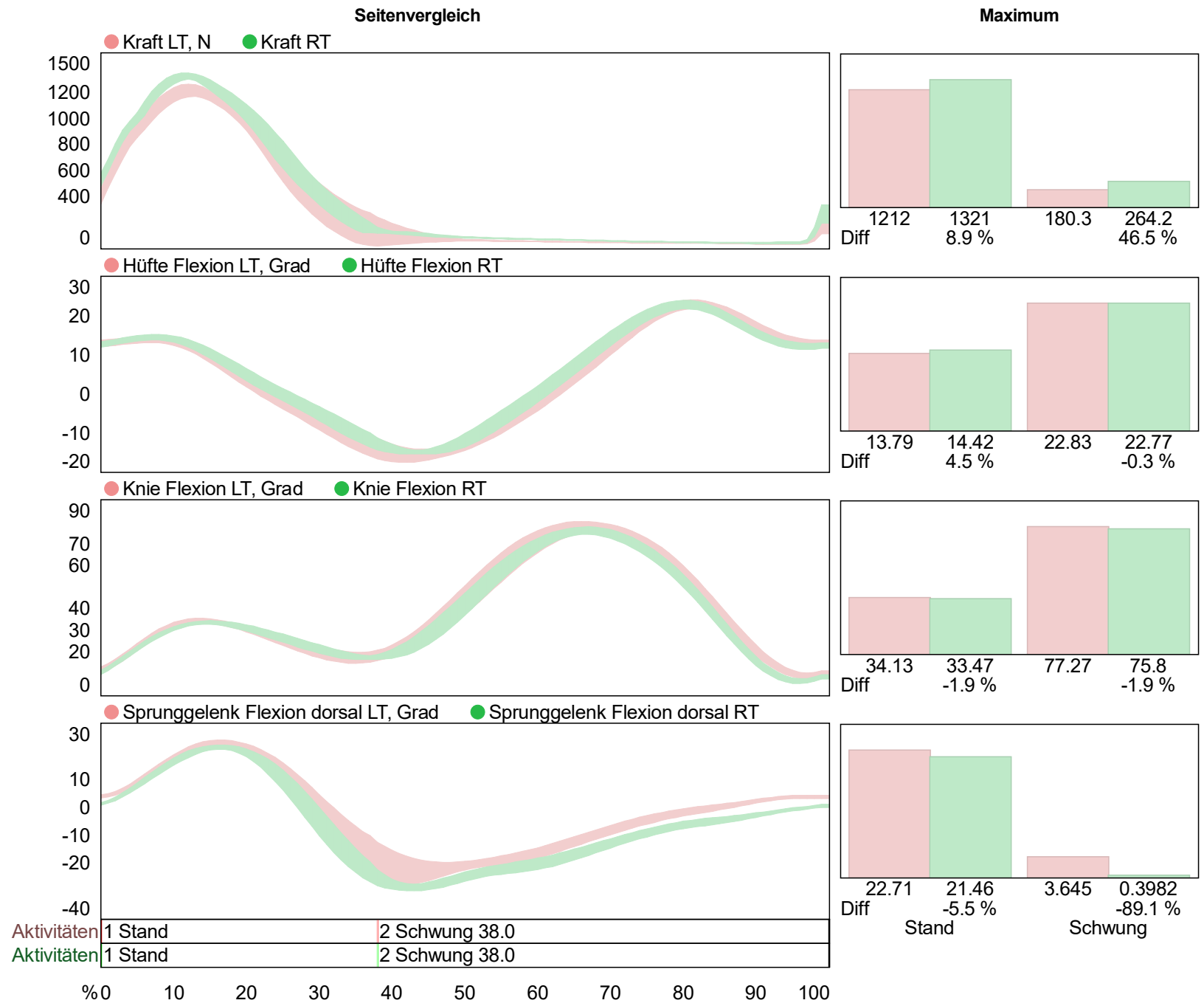
Laufphasen Parameter

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	Rechts	38.1±2.1
	Diff, %	1.4
Einbeinstandphase, %	Links	37.6±3.2
	Rechts	38.2±2.1
	Diff, %	1.5
Schwungphase, %	Links	62.4±3.2
	Rechts	61.9±2.1
	Diff, %	-0.8

Zeitliche Parameter

Schrittzeit, ms	Links	373±5
	Rechts	368±4
	Diff, %	-1.3
Zeit Doppelschritt, ms		741±6
Kadenz, Schritte/min		162±1

[redacted]



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SAGITTAL (Kinematics & Forces, Running Analysis at 9 km/h)

Temporal Parameters

- Stance phase: Left 37.6% | Right 38.1% (difference ~1–1.5%)
- Step time and cadence: highly symmetrical

Conclusion: No evidence of unloading or compensatory gait on the left side.

Joint Angles

- Hip flexion: symmetrical
- Knee flexion: nearly identical
- Ankle joint: minimal differences limited to swing phase (clinically irrelevant)

Conclusion: Kinematically clean and symmetrical running pattern.

DORSAL (Hamstrings & Gluteus Medius)

Biceps Femoris & Semitendinosus

- Physiological activation pattern:
  - Early stance phase (knee/tibial control)
  - Late swing phase (deceleration)
- Side differences:
  - Slightly higher amplitudes on the left
  - Identical timing

Conclusion: Findings indicate functional adaptation rather than deficit. This pattern is typical after conservative ACL management, reflecting a coordinated protective strategy.

Gluteus Medius

- Good activation during stance phase
- Side differences:
  - Stance phase: slightly higher on the left
  - Swing phase: nearly identical

Conclusion: Excellent pelvic stability with no evidence of a Trendelenburg pattern.

VENTRAL (Quadriceps Activation Pattern)

This domain shows the most relevant adaptations.

Vastus Lateralis Obliquus (VLO) / Rectus Femoris / Vastus Medialis Obliquus (VMO)

- Right (uninjured side): higher EMG amplitudes
- Left (ACL-injured side): lower amplitudes
- Timing: fully synchronous

Key point: No delayed or absent activation on the left- only reduced amplitude with preserved timing.

Interpretation: Force production is achieved through efficient coordination rather than sustained high activation.

Clinical relevance:

- No quadriceps-dominant protective strategy
- No indication of increased anterior tibial shear forces (ACL loading)

Key Messages from EMG Findings

1. No pathological activation patterns in any plane (sagittal, dorsal, ventral).
2. Timing and phase relationships of all muscles are bilaterally synchronous.
3. The previously injured (left) side demonstrates efficient activation rather than avoidance.
4. Hamstring and gluteal activity actively contribute to dynamic knee stability.
5. The ventral chain shows no quadriceps overdominance, which is ACL-protective.

Integration with RTS / RTC Findings

Domain	**Result**
Isokinetics	Symmetrical strength and work output
Hop & balance tests	>90–100%, RTS-ready
Subjective perception	No instability
EMG	Clean, efficient neuromuscular coordination

Conclusion: No discrepancy between strength, functional performance, and neuromuscular control.

Critical insight:

- EMG confirms that strength capacities are functionally utilized
- No evidence of “hidden compensations,” which are often present despite good hop test performance

SUMMARY

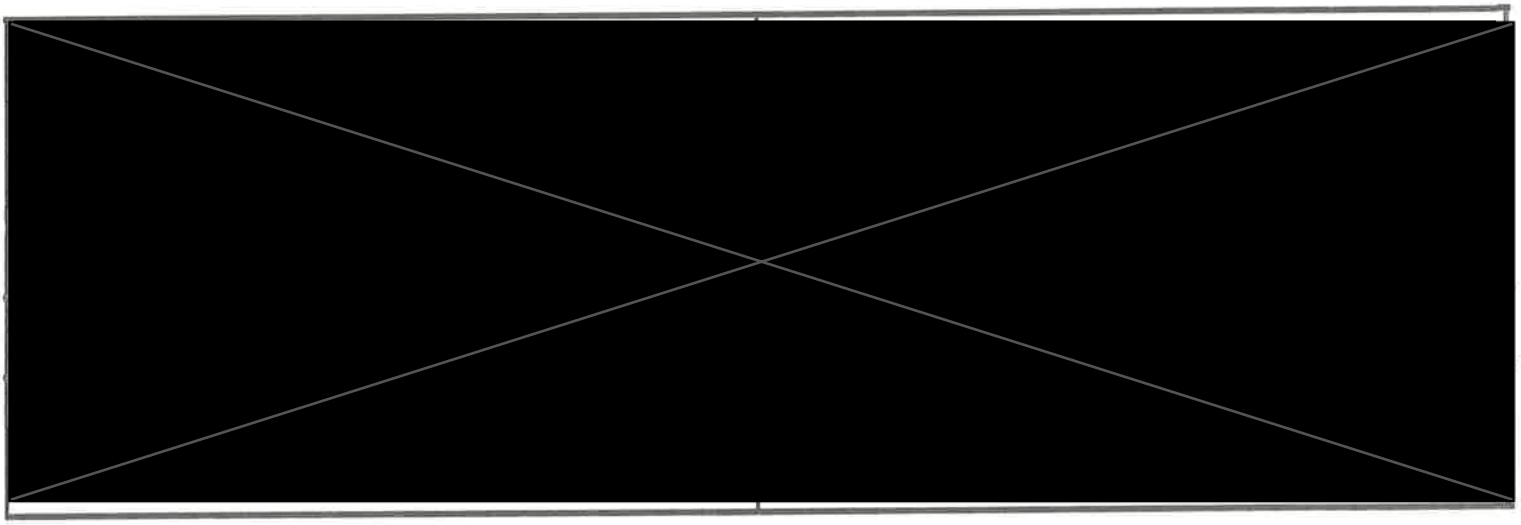
The EMG running analysis (sagittal, dorsal, ventral) demonstrates bilaterally synchronous activation patterns without pathological delays or compensatory strategies.
The previously injured left side exhibits efficient, non-overprotective muscle activation, with strong hamstring and gluteal contribution and no quadriceps-dominant pattern.
In conjunction with the functional RTS testing, there are no neuromuscular indicators of increased re-injury risk.

Bottom Line

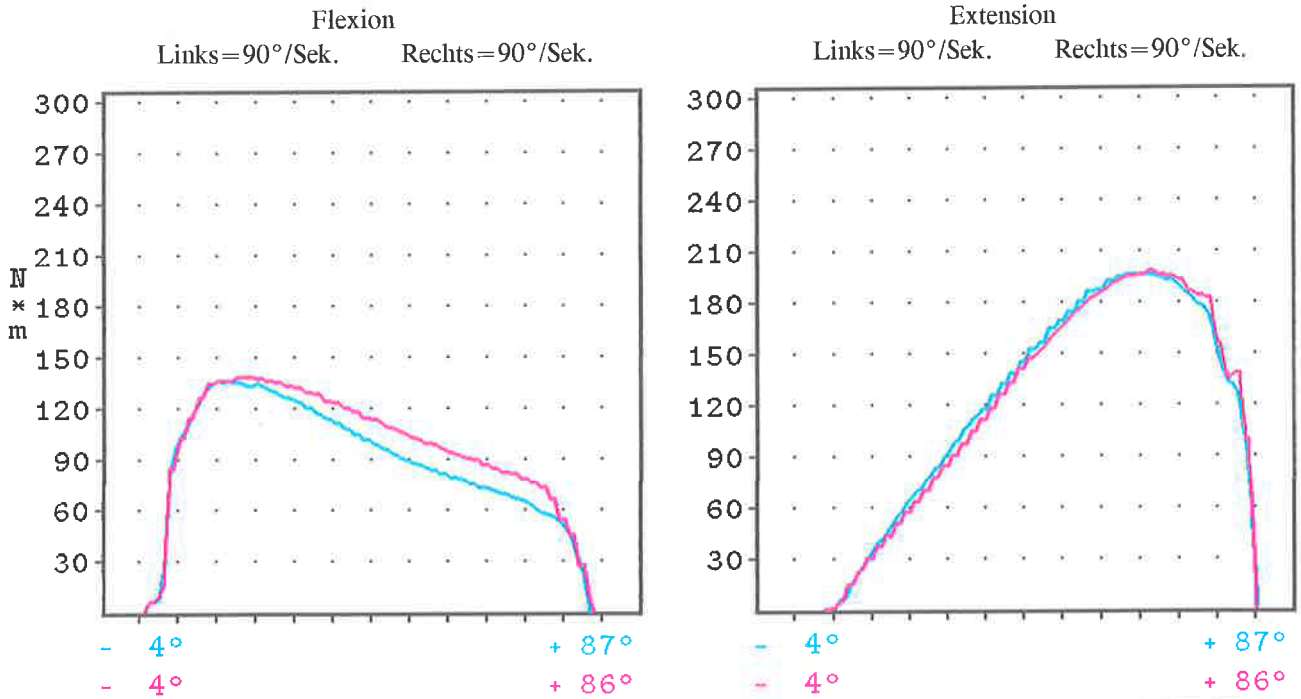
- No unloading behaviour, no protective patterns, no maladaptive coordination
- Neuromuscular control aligns excellently with RTS outcomes
- From an EMG perspective, there is no additional re-injury risk for field hockey

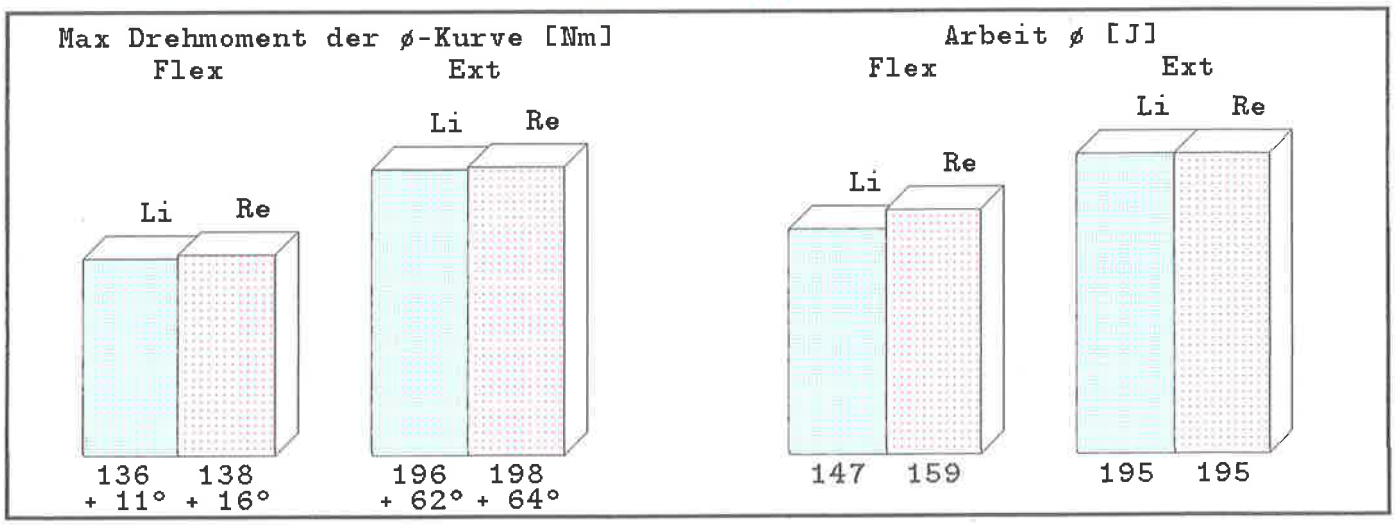
2. Isokinetic strength testing

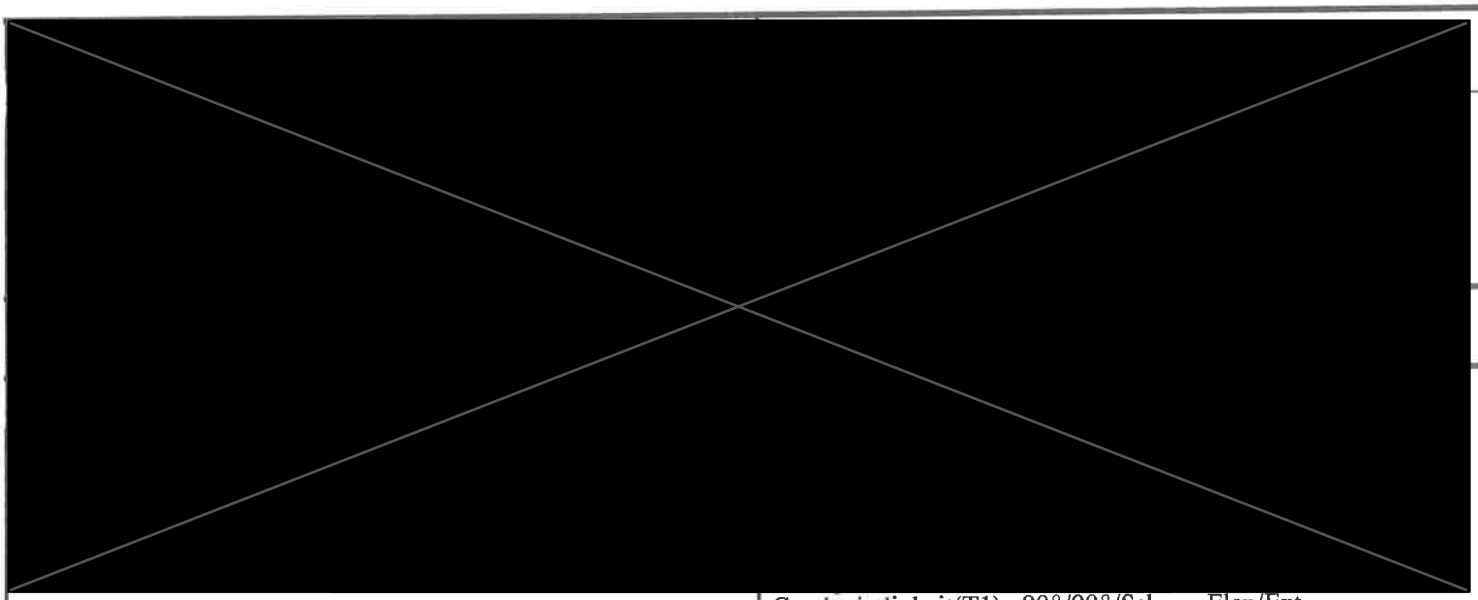
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Durchschnittskurve:Links (Wdh 1 - 8)
Durchschnittskurve:Rechts (Wdh 1 - 8)







Kostenträger :
Überweisung :

Geschwindigkeit(T1) : 90°/90°/Sek. Flex/Ext
Geschwindigkeit(T2) : 90°/90°/Sek. Flex/Ext
Uhrzeit : 11:49

Bewegung: Knie Flexion/Extension	Links (T1) Datum : 15.05.2024 Zeit : 11:20 Sätze : 2 Kal.Satz : 2	Rechts (T2) Datum : 15.05.2024 Zeit : 11:24 Sätze : 2 Kal.Satz : 2	T1/T2 % (T2/T1) %
Drehmoment max. Flex (Wdh): an Position: Arbeit max. Flex (Wdh):	144 Nm (3) + 12 ° 156 J (2)	147 Nm (3) + 12 ° 169 J (1)	97.7 (102.4) % 92.3 (108.3) %
Drehmoment max. Ext (Wdh): an Position: Arbeit max. Ext (Wdh):	213 Nm (2) + 62 ° 210 J (2)	213 Nm (2) + 64 ° 213 J (2)	100.6 (99.4) % 98.6 (101.4) %
Drehmoment max. d. Durchschnittsk. Flex Drehmoment max. d. Durchschnittsk. Ext	136 Nm 196 Nm	138 Nm 198 Nm	98.5 (101.5) % 99.0 (101.0) %
Drehmoment max. Flex/Ext (Ext /Flex): Arbeit max. Flex/Ext (Ext /Flex):	67.2 (148.7) % 74.3 (134.6) %	69.2 (144.4) % 79.6 (125.7) %	97.1 (103.0) % 93.3 (107.1) %
Drehmoment max. Flex /Gewicht: Drehmoment max. Ext /Gewicht:	1.80 Nm/kg 2.66 Nm/kg	1.84 Nm/kg 2.66 Nm/kg	97.7 (102.4) % 100.6 (99.4) %
Arbeit max. Flex /Gewicht: Arbeit max. Ext /Gewicht:	1.95 J/kg 2.63 J/kg	2.11 J/kg 2.66 J/kg	92.0 (108.7) % 98.6 (101.4) %
Arbeit durchschnitt Flex Arbeit durchschnitt Ext	146.8 J 195.4 J	159.4 J 195.4 J	92.1 (108.6) % 100.0 (100.0) %
Arbeit gesamt Flex: Arbeit gesamt Ext :	1174 J 1563 J	1275 J 1563 J	92.1 (108.6) % 100.0 (100.0) %
Leistung max. Flex (Wdh): Leistung max. Ext (Wdh):	133 W (2) 187 W (2)	144 W (3) 193 W (2)	92.7 (107.9) % 96.9 (103.2) %
Leistung durchschnitt Flex: Leistung durchschnitt Ext :	124 W 174 W	132 W 175 W	94.3 (106.0) % 99.1 (100.9) %
Bewegungsende 1: Bewegungsende 2: (Aufspannung)	- 4 ° + 87 ° (91 °)	- 4 ° + 86 ° (90 °)	101.1 (98.9) %
Anzahl Wiederholungen des Satzes: Kalkulierte Wiederholungen des Satzes:	8 Wdh. 1 - 8	8 Wdh. 1 - 8	

The figure is derived from an isokinetic knee assessment (IsoMed 2000).

Test conditions:

- Movement: Knee flexion and extension
- Angular velocity: 90°/s
- Comparison: Left vs. right leg
- Data representation: Mean of 8 repetitions

The curves illustrate torque (Nm) over joint angle (°).

Left Graph – Flexion

- x-axis: Joint angle (approx. 4° to ~87°)
- y-axis: Torque (Nm)
- Curves: Blue = left | Pink = right

Interpretation:

- Both sides reach peak torque early in the range of motion
- Torque gradually decreases thereafter
- Curves are highly similar, with slightly higher values on the right

Conclusion: Hamstring strength is nearly symmetrical, with a minimal advantage on the right side.

Right Graph – Extension

- Same axes as flexion
- Torque increases progressively throughout the movement
- Peak torque occurs near terminal extension

Interpretation:

- Highly symmetrical curve profiles
- Left and right sides are nearly superimposable
- No drops or asymmetries

Conclusion: Quadriceps strength is bilaterally consistent and stable.

Bar Charts – Quantitative Values

a) Peak Torque (Nm)

- Flexion: Left 136 Nm Right 138 Nm
- Extension: Left 196 Nm Right 198 Nm

Conclusion: Side-to-side differences <2% → clinically insignificant

b) Work (Joules)

- Flexion: Left 147 J Right 159 J
- Extension: Left 195 J Right 195 J

Conclusion:

- Extension: perfectly symmetrical
- Flexion: slightly higher work on the right, still within normal limits

Key Messages from the Figure

1. Very good left-right symmetry in both flexion and extension
2. No relevant strength asymmetry (>10%)

3. Quadriceps (extension) particularly stable and consistent
4. Hamstrings (flexion) slightly stronger on the right, but not pathological
5. Physiological and smooth torque curves across the full range of motion

Overall Sports Medicine Evaluation (Current Status)

Key Findings

Quadriceps (Extension):

- Peak torque: 196 Nm (left) vs. 198 Nm (right)
- Total work: 1563 J (left) = 1563 J (right)
- Side difference: ≈0–1%

Hamstrings (Flexion):

- Peak torque: 136 Nm (left) vs. 138 Nm (right)
- Total work: 1174 J (left) vs. 1275 J (right)
- Work difference: ~8%

Hamstring-to-Quadriceps Ratio (H/Q):

- Left: ≈67%
- Right: ≈69%
  → within a favorable athletic range

Interpretation

For a conservatively managed ACL injury, this represents an excellent long-term outcome:

- No persistent quadriceps deficit (commonly observed after ACL injury)
- Functionally stable hamstrings
- Symmetrical strength and work profiles

Conclusion: No indication of strength-related functional instability.

Rehabilitation Evaluation (Retrospective & Current)

Positive Aspects

- No quadriceps inhibition pattern on the left
  → a frequent issue post-ACL injury, not present here
- Smooth and consistent torque production across the full range of motion
- High load tolerance (8 repetitions without performance drop-off)

Minor Finding

- Slightly reduced hamstring work on the left
  → typical compensatory pattern, but:
  - Difference <10%
  - H/Q ratio remains stable

Conclusion: Rehabilitation goals can be considered fully achieved. No muscular limitations for return to sport.

Return-to-Sport (RTS) – Differentiated Evaluation

Criteria Fulfilled

RTS Criterion	Status
LSI strength (≥90%)	Achieved (≈98–100%)
Quadriceps symmetry	Yes
H/Q ratio ≥60%	Yes (67–69%)
No performance decline	Yes
Symmetrical extension work	Yes

Important Limitation of Isokinetic Testing: Isokinetic testing assesses isolated muscle strength, but does not capture:

- Tibial translation
- Rotational stability
- Reactive neuromuscular control
- Valgus or landing mechanics
- Fatigue under sport-specific conditions

These factors are particularly critical following conservative ACL management.

Short Conclusion

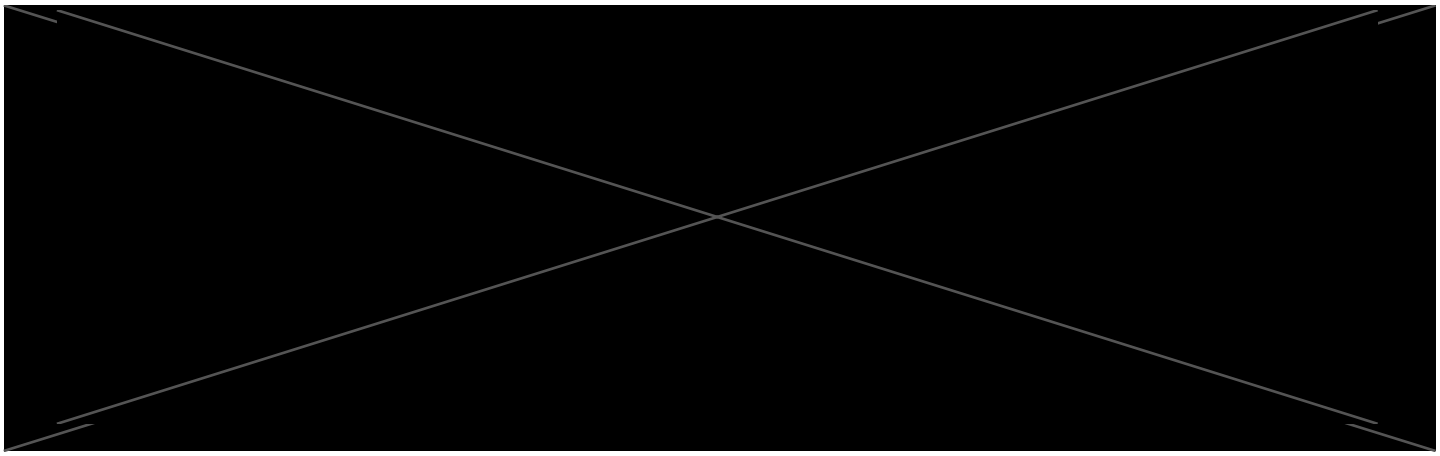
For a conservatively managed left ACL rupture (2021):

- Excellent muscular outcome
- RTS is justified from a strength perspective
- Neuromuscular control remains the key determinant for high-risk sports

Bottom Line

- The knee demonstrates full performance capacity and sport readiness
- No evidence of residual deficits related to the ACL injury
- No medical indication for activity restriction
- Prevention strategies serve performance optimization, not rehabilitation

3. Functional performance tests (Y-Balance, hop tests, jump analysis)

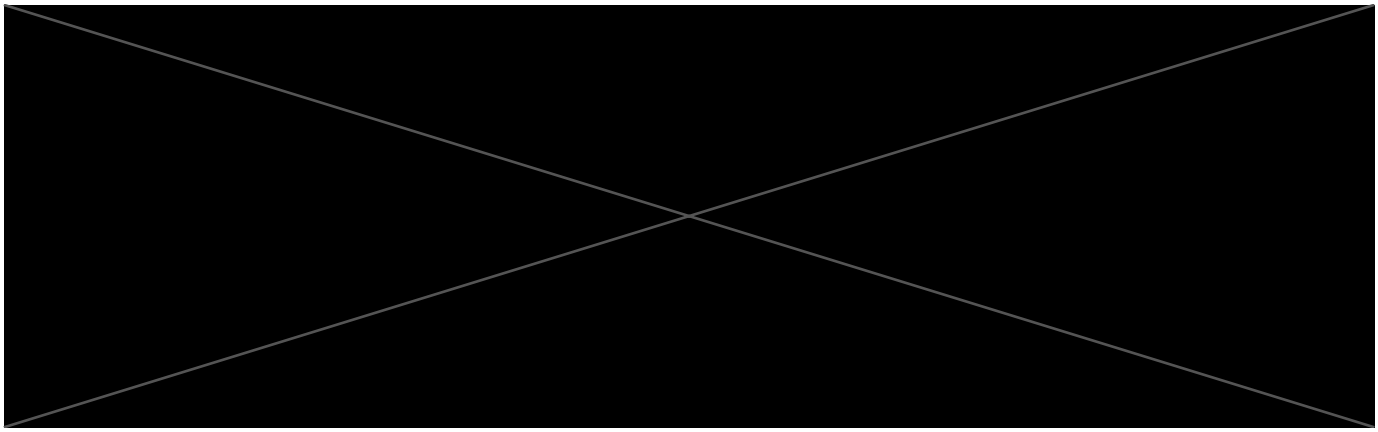


Y-Balance Test

Beinlänge [cm]: 95

	Rechts	Links
Anterior	56	56
Posteromedial	116	114
Posterolateral	105	105

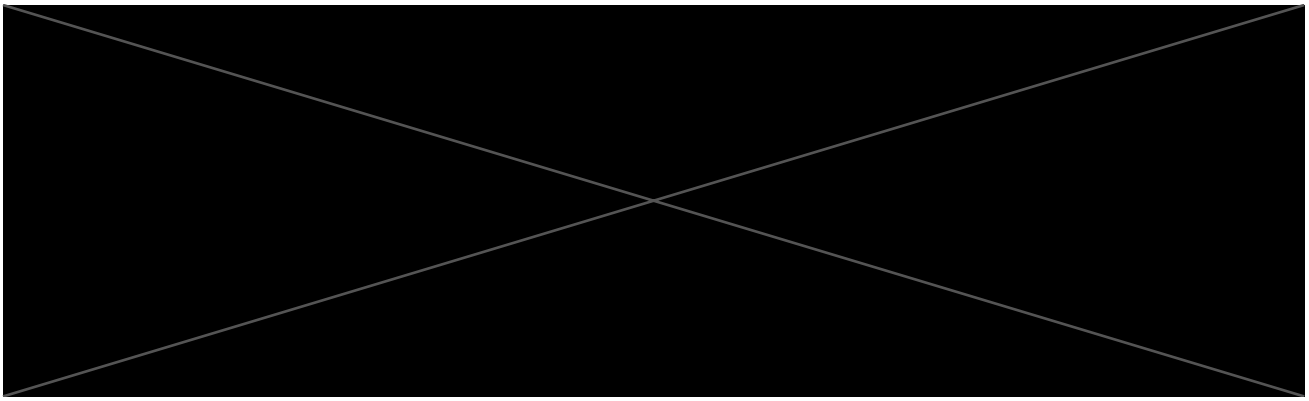
			Norm
Score	**97,2**	**96,5**	**≥ 95**
Seitenvergleich [%]	**-0,7**		**≤ 5%**



Isokinetik - Offene Kette

Testgelenk: Knie Extension/Flexion 60°/s

	R	L	Differenz
Drehmoment max. Flexion [Nm]:	**159**	**174**	**9,4**
Drehmoment max. Extension [Nm]:	**237**	**252**	**6,3**
Drehmoment max. Flex./Ext. [%]:	**67,1**	**69,2**	
Drehmoment max. Ext./Gewicht [Nm/kg KG]:	**2,96**	**3,15**	
Arbeit durchschn. Flexion [J]:	**176,2**	**186,6**	**5,9**
Arbeit durchschn. Extension [J]:	**245,5**	**240,9**	**-1,9**



Counter Movement Jump (bilateral)

1. Vers. [cm]	2. Vers. [cm]	
39,8	40,9	

Counter Movement Jump (unilateral)

Rechts [cm]	Links [cm]	LSI [%]
20,5	19,6	95,6

Drop Down Landing

COP - Weglänge		
Rechts [mm]	Links [mm]	LSI [%]
420	368	87,6

Side-Hop-Test (30 Sek.)

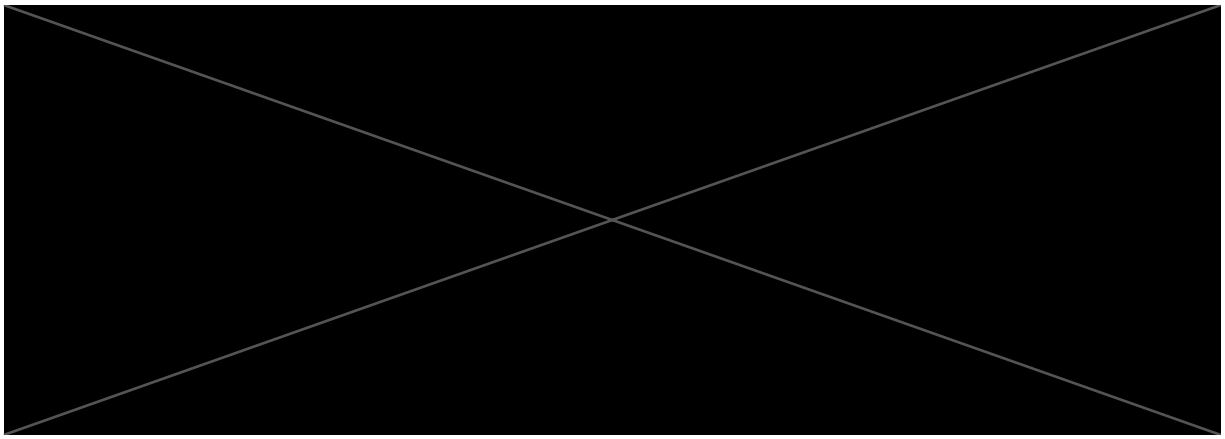
Rechts [n]	Links [n]	LSI [%]
73	79	92,4

Single-Leg-Hop-For-Distance

Körpergröße [cm]: 180

Rechts [cm]	Links [cm]	LSI [%]
199	200	99,5

Beurteilung [cm]	
♂	♀
162	144
144	126



Isometrie Hüftmuskulatur

Datum	Gewicht	rel. Isometrische Maximalkraft [kg/kg KG]			
	[kg]	Extension	Flexion	Abduktion	Adduktion
17.4.2024	80,0	58,00	52,15	51,95	0,48

SUMME
162,58
0,00

Extension

Rechts [kg]	Links [kg]	Differenz [%]	rel. Kraft [kg/kg KG]
55,7	60,3	-7,6	0,73

Flexion

Rechts [kg]	Links [kg]	Differenz [%]	rel. Kraft [kg/kg KG]
51,4	52,9	-2,8	0,65

Abduktion

Rechts [kg]	Links [kg]	Differenz [%]	rel. Kraft [kg/kg KG]
50,7	53,2	-4,7	0,65

Adduktion

Rechts [kg]	Links [kg]	Differenz [%]	rel. Kraft [kg/kg KG]
62,5	65,1	-4,0	0,80

1. Individual Analysis of RTS Components

Y-Balance Test

Normative criteria

- Composite score ≥95%
- Side-to-side difference ≤5%

Results

- Anterior: 97–98%
- Posteromedial / posterolateral: 105–114%
- Side-to-side difference: −0.7%
- Composite score: 116%

Evaluation

- Clearly above normative thresholds
- No asymmetry
- Excellent anteroposterior and rotational control

Conclusion: Outstanding performance for a conservatively managed ACL injury, particularly relevant for low, dynamic field hockey positions.

Isokinetic Testing (Open Chain, 60°/s)

- Extension torque: ≈245 Nm
- Flexion torque: ≈175 Nm
- Flexion/extension ratio: ≈69%
- Side-to-side difference: <3%
- Work (flexion & extension): symmetrical

Evaluation

- Very good maximal strength
- Hamstring-dominant protective profile
- No indication of quadriceps or hamstring deficit on the left

Conclusion: Complements previous 90°/s isokinetic testing; strength capacity is fully RTS-eligible.

Hop and Jump Tests

Single Leg Hop for Distance: LSI: 99.5%
Conclusion: Excellent, near-perfect symmetry

Side Hop Test (30 s): LSI: 92.4%
Conclusion: Slightly reduced output on the left under time pressure, consistent with reactive fatigue rather than structural deficit

Countermovement Jump (CMJ)

- Bilateral and unilateral values within normal range
- No relevant side dominance

Drop Down Landing

- Jump height L/R: 95.6%
- COP path length LSI: 87.6%

Conclusion:

Mechanically stable; left side slightly "quieter," with no valgus or control deficits

Isometric Hip Strength

(Hip extension / flexion / abduction / adduction)

- Side-to-side differences: 2–8%
- Relative strength values within athletic normative ranges

Conclusion:

Adequate pelvic and lower limb chain stability; no proximal contribution to knee instability

2. Overall RTS Evaluation for Field Hockey

- All key criteria ≥90%
- No pathological asymmetries
- Good fatigue resistance and reactive capacity
- No subjective complaints

3. Key Messages

1. No relevant side-to-side asymmetries in strength, balance, or jump performance following conservatively managed ACL rupture (left).
2. Y-Balance and hop tests exceed established RTS thresholds, indicating strong neuromuscular control.
3. Hamstring-to-quadriceps ratio is favorable for the sport and supports dynamic ACL stabilization.
4. Minor performance reductions under time pressure (side hop) are not structurally relevant and have no clinical implications.
5. From a functional perspective, full clearance for training and competition in field hockey is justified.

Return-to-Sport Summary (RTS)

1. Strength Diagnostics

Knee (isokinetics, open & closed kinetic chain)

- Quadriceps: no relevant side-to-side asymmetry (LSI ≈ 98–100%)
- Hamstrings: symmetrical strength and work values
- H/Q ratio: approx. 67–69%, favorable for sport-specific demands
- No decline in force over repeated efforts

Assessment: Excellent maximal strength and load tolerance, no ACL-relevant deficit.

2. Balance & Neuromuscular Control

Y-Balance Test

- Composite score: >115%
- Side-to-side difference: <1%
- All directions clearly above normative values

Assessment: Excellent static-dynamic lower limb alignment and pelvic stability, highly relevant for low hockey positions.

3. Jump & Plyometric Testing

- Single-Leg Hop for Distance: LSI ~100%
- Side Hop (30 s): LSI ~92%
- Countermovement Jump: bilateral & unilateral within normal range
- Drop Down Landing: stable landing, no pathological movement patterns

Assessment: Good reactive strength and landing control. Slightly reduced performance under time constraints without clinical relevance.

4. Proximal Stability (Hip)

- Isometric hip strength (flexion/extension/abduction/adduction):
    - Side-to-side differences <8%
    - Relative strength values within athletic normative range

Assessment: No proximal weakness as a risk factor for the knee.

5. Overall Return-to-Sport Assessment

- No relevant asymmetries in strength, balance, or jump performance
- Very high level of neuromuscular control
- Favorable hamstring-to-quadriceps ratio
- No subjective complaints or instability

Conclusion: From a functional and sports medicine perspective, full clearance for training and competition in field hockey is granted.