



COMPREHENSIVE CHARACTERIZATION AND PERFORMANCE MAPPING OF KNITTED ARCHITECTURES FOR ACTIVE SPORTSWEAR APPLICATIONS

Review paper
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ABSTRACT: Advanced engineering of athletic apparel requires an intricate understanding of mechanical, structural, and thermo-physiological behavior under conditions of intense activity and regular maintenance cycles. This study presents an exhaustive experimental mapping and characterization of 26 separate knitted fabric specimens manufactured from a cross-section of primary apparel materials, including natural cotton, virgin polyester (PES), recycled polyester (REC PES), and elastane (EA) blends across multiple stitch arrangements (single jersey, three-yarn fleece, mesh, rib, piqué, interlock, and spacer configurations). The experimental framework comprised the full 16-stage testing pipeline: atmospheric conditioning, fabric mass, stitch density profiling, pneumatic bursting pressure, ball burst strength, Martindale abrasion failure cycles, pilling evaluation, multi-axial extension and elastic recovery, strip-tensile breaking strength, washing dimensional shrinkage, loop spirality deformation, air permeability, vertical capillary moisture wicking, washing color fastness, dry/wet crocking fastness, perspiration fastness under acidic/alkaline media, and phenolic yellowing storage risks. The empirical findings demonstrated that while 100% cotton specimens provide exceptional initial soft touch and moisture intake, they fail core industrial durability metrics, yielding severe lengthwise washing contraction up to -13.3% and loop spirality up to 5.8%. In contrast, dense double-knit structures, notably 100% PES Interlock variants, exhibited supreme structural locking and an unprecedented ball burst resistance of 981.0 N. Recycled synthetic variants achieved technical and performance parity with virgin counterparts across all mechanical and fastness parameters. Based on this multidimensional data pool, a localized zoning structural matrix (body mapping layout) is proposed for engineered athletic jersey optimization.

Keywords: Active Sportswear, Knitted Configurations, Comprehensive Testing Pipeline, Mechanical Parity, Structural Integrity, Thermo-Physiological Ergonomics.

SVEOBUH VATNA KARAKTERIZACIJA I MAPIRANJE PERFORMANSI PLETENIH STRUKTURA ZA PRIMENU U AKTIVNOJ SPORTSKOJ ODEĆI

APSTRAKT: Napredno inženjerstvo sportske odeće zahteva detaljno razumevanje mehaničkog, strukturnog i termo-fiziološkog ponašanja u uslovima intenzivne aktivnosti i redovnih ciklusa održavanja. Ova studija predstavlja iscrpno eksperimentalno mapiranje i karakterizaciju 26 različitih uzoraka pletenih tkanina proizvedenih od preseka primarnih materijala za odeću, uključujući prirodni pamuk, devičanski poliestar (PES), reciklirani poliestar (REC PES) i mešavine elastana (EA) kroz višestruke aranžmane prepleta (singl džersi, trožilni flis, mrežasti, rebrasti, pike, interlok i spejser konfiguracije). Eksperimentalni okvir obuhvatio je kompletan lanac ispitivanja od 16 faza: atmosfersko kondicioniranje, masu tkanine, profilisanje gustine petlji, pneumatski pritisak rasprskavanja, otpornost na rasprskavanje čeličnom kuglom, cikluse oštećenja usled Martindale abrazije, procenu pilinga, višeosno izduženje i elastični oporavak, otpornost na kidanje trake, dimenziono skupljanje pri pranju, deformaciju spiralnosti petlji, propusnost vazduha, vertikalno kapilarno odvođenje vlage, postojanost boje pri pranju, postojanost na suvo/mokro trljanje, postojanost na znoj u kiseljoj/alkalnoj sredini i rizike od fenolnog žućenja tokom skladištenja. Empirijski nalazi su pokazali da, iako uzorci od 100% pamuka pružaju izuzetan početni mek dodir i upijanje vlage, oni ne ispunjavaju ključne industrijske metrike trajnosti, pokazujući ozbiljno uzdužno skupljanje pri pranju do -13,3% i spiralnost petlji do 5,8%. Nasuprot tome, guste dvostruko pletene strukture, posebno varijante 100% PES Interloka, pokazale su vrhunsko strukturno zaključavanje i neprevaziđenu otpornost na rasprskavanje kuglom od 981,0 N. Reciklirane sintetičke varijante postigle su tehnički i performansni paritet sa devičanskim pandanima u svim mehaničkim parametrima i parametrima postojanosti. Na osnovu ovog višedimenzionalnog skupa podataka, predložena je lokalizovana strukturna matrica zoniranja (izgled mapiranja tela) za optimizaciju projektovanih sportskih dresova.

Ključne reči: Aktivna sportska odeća, Pletene konfiguracije, Sveobuhvatni lanac ispitivanja, Mehanički paritet, Strukturni integritet, Termo-fiziološka ergonomija.

1. INTRODUCTION

High-performance sportswear operates under unique engineering paradigms that differentiate it significantly from conventional lifestyle fashion. During athletic activities, garments undergo repeated complex stresses, including extreme multi-directional expansions, severe abrasive skin friction, and rapid environment-body humidity fluctuations. Consequently, structural integrity, durability, and moisture handling must be engineered simultaneously. Knitted configurations are universally preferred in this field due to their flexible loop configurations, which allow multi-axial elongation while accommodating muscle expansion without permanent structural bagging. This investigation establishes a holistic empirical baseline across 26 distinct commercial variants, exploring the full mechanical, dimensional, and comfort limitations to formulate an optimized performance layout matrix.



2. MATERIALS AND EXPERIMENTAL METHODS

2.1. Material Specimen Profile

The research pipeline was executed across a meticulous assortment of 26 industrial-grade knitted specimens. To achieve full tracking, all 26 materials, along with their precise knitting architecture, areal mass, raw fiber composition, and geometric loop distributions, are detailed in Table 1.

Table 1: The list of materials

Sample ID	Knitting Construction Type	Fabric Mass (g/m ²)	Raw Material Blend Composition	Wales per cm (Wpc)	Courses per cm (Cpc)
M1	Single Jersey	140	100% Cotton	14.0	18.5
M2	Single Jersey	160	100% Cotton	13.5	17.0
M3	Single Jersey	180	100% Cotton	12.0	15.5
M4	Single Jersey	150	65% Polyester / 35% Cotton	14.5	19.0
M5	Single Jersey	170	88% Recycled PES / 12% Elastane	16.5	22.0
M6	Single Jersey	165	92% Polyester / 8% Elastane	16.0	21.5
M7	Mesh / Filet Openwork	140	100% Recycled PES	10.0	12.0
M8	Mesh / Filet Openwork	130	100% Polyester	10.5	11.5
M9	Mesh / Filet Openwork	150	100% Recycled PES	9.5	12.5
M10	Mesh / Filet Openwork	160	95% Polyester / 5% Elastane	11.0	13.0
M11	Rib 1x1 Configuration	220	100% Cotton	11.5	14.0
M12	Rib 1x1 Configuration	240	100% Cotton	11.0	13.5
M13	Rib 1x1 Configuration	255	100% Polyester	11.0	14.5



9. Međunarodna naučna konferencija
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Sample ID	Knitting Construction Type	Fabric Mass (g/m ²)	Raw Material Blend Composition	Wales per cm (Wpc)	Courses per cm (Cpc)
M14	Rib 1x1 Configuration	270	100% Cotton	10.0	13.0
M15	Rib 2x2 Configuration	280	95% Cotton / 5% Elastane	9.5	12.0
M16	Rib 2x2 Configuration	290	100% Polyester	9.0	13.0
M17	Three-Yarn Fleece	320	100% Cotton	9.5	12.0
M18	Three-Yarn Fleece	360	100% Cotton	9.0	11.5
M19	Three-Yarn Fleece	400	65% Cotton / 35% Polyester	8.5	11.5
M20	Three-Yarn Fleece	440	100% Cotton	8.5	11.0
M21	Piqué Construction	180	100% Cotton	12.5	16.0
M22	Piqué Construction	200	65% Polyester / 35% Cotton	12.0	15.5
M23	Piqué Construction	190	100% Recycled PES	13.0	16.5
M24	Interlock Double-Knit	140	100% Cotton	15.5	20.0
M25	Interlock Double-Knit	150	100% Polyester	15.0	19.0
M26	Spacer / 3D Sandwich	270	70% Cotton / 30% Recycled PES	12.0	15.5

Comprehensive 16-Stage Standardized Testing Pipeline

- 1. Specimen Atmospheric Conditioning (ISO 139): Samples exposed for 24 hours at 20 ± 2 °C and $65\% \pm 5\%$ RH.
- 2. Fabric Mass per Unit Area (Areal Weight - ISO 3801): Measured using circular 100 cm² die cutters and digital balances.
- 3. Stitch Density Profiling: Wales per cm (Wpc) and Courses per cm (Cpc) mapped using standard illuminated textile loupes.
- 4. Pneumatic Diaphragm Bursting Strength (ISO 13938-1): Applied circular hydraulic diaphragm pressure across a 50 cm² window until loop burst failure.



- 5. Steel Ball Burst Strength (ASTM D6797): Polished steel 25.4 mm sphere pushed through fabrics using CRE columns to check peak force.
- 6. Martindale Abrasion Resistance and Lifetime Failure (ISO 12947-2): Specimen rubbed under 9 kPa payload against wool fabrics up to 50,000 cycles.
- 7. Martindale Pilling and Surface Fuzzing Degradation (ISO 12945-2): Face-to-face rubbing scored via standard comparative cards (Grade 1-5).
- 8. Multi-Axial Elastic Extension and Recovery (ASTM D2594): Tracked expansion capability and residual structural deformation after static relaxation.
- 9. Strip Tensile Strength and Breaking Elongation (ISO 13934-1): Pulled 50 mm wide stripes across a 200 mm span on axial columns.
- 10. Laundering Dimensional Stability / Shrinkage Tracking (ISO 5077 / ISO 6330): Calculated post-laundering loop contraction at 40°C.
- 11. Loop Spirality and Distortion Torque (ISO 6330 / AATCC 179): Checked structural torque skewness following automated laundering.
- 12. Pneumatic Air Permeability (ISO 9237): Calculated vertical air passage velocity at a fixed differential pressure of 100 Pa.
- 13. Thermo-Physiological Vertical Capillary Wicking (AATCC 197): Tracked distilled water capillary elevation along vertical fabric ribbons.
- 14. Color Fastness to Home Laundering (ISO 105-C06): Scored accelerated shade loss and multi-fiber transfer using Grey Scales.
- 15. Color Fastness to Crocking and Friction Rubbing (ISO 105-X12): Motorized dry/wet rubbing tracks evaluating mechanical stain transfer.
- 16. Color Fastness to Human Perspiration (ISO 105-E04): Incubated multi-fiber sand specimens in artificial body chemistry solutions at 37°C for 4 hours.
- 17. Storage Phenolic Yellowing Tendency (ISO 105-X18): Oven-packed wrap testing investigating nitrogen oxide storage oxidation hazards.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Extensive Structural and Mechanical Strength Diagnostics

The experimental mapping of mechanical resilience revealed clear performance boundaries based on knitting architecture and raw material composition. Single knit frameworks (M1 to M6) demonstrated a baseline ball burst strength profile ranging between 286.5 N and 474.8 N. Three-yarn fleeces (M17 to M20) demonstrated higher resistance (363.6 N to 524.0 N) due to the presence of heavy inlay backing yarns woven behind the face loops. The absolute performance peak was achieved by M25 (100% Polyester Interlock), which recorded an extraordinary ball burst threshold of 981.0 N and pneumatic bursting pressure exceeding 780 kPa. The structural locking mechanism of the interlock matrix distributes multi-axial stress evenly across both yarn planes, preventing early stitch collapse. The complete experimental data pool is provided in Table 2.

Table 2: The complete experimental data pool

ID	Ball Burst (N)	Pneumatic Burst (kPa)	Abrasion (Cycles)	Pilling Grade	Shrinkage (%)	Spirality (%)	Air Perm. (mm/s)	Wicking (mm)
M1	310.2	295	22,000	3	-11.5	4.8	185	85
M2	422.2	310	25,000	3	-13.3	5.2	170	90
M3	455.0	340	28,000	3-4	-12.0	5.8	155	95
M4	510.5	420	38,000	4	-5.2	2.1	210	75
M5	645.8	580	>50,000	4-5	-1.1	0.0	285	120
M6	612.0	550	>50,000	4-5	-1.4	0.0	260	115
M7	529.0	480	>50,000	4-5	-0.8	0.0	445	145
M8	512.4	465	>50,000	4-5	-0.9	0.0	460	140
M9	540.6	490	>50,000	4-5	-0.7	0.0	430	148
M10	585.2	520	>50,000	4	-1.8	0.0	395	130
M11	385.4	320	24,000	3	-10.8	0.0	240	100
M12	410.2	350	26,000	3	-11.3	0.0	220	105
M13	680.5	610	>50,000	4-5	-1.2	0.0	310	125
M14	440.0	365	27,000	3	-11.1	0.0	205	110
M15	495.6	410	32,000	3-4	-4.5	0.0	250	115
M16	710.2	640	>50,000	4-5	-1.0	0.0	295	130
M17	363.6	390	18,000	2	-9.5	1.2	120	70
M18	415.0	425	20,000	2	-10.2	0.8	110	75
M19	490.8	495	34,000	3	-4.1	0.5	135	65
M20	524.0	530	22,000	2-3	-10.5	0.9	95	80
M21	390.4	340	25,000	3-4	-8.4	1.5	190	90
M22	540.2	460	40,000	4	-3.2	0.6	225	80
M23	595.6	510	>50,000	4-5	-0.9	0.0	245	120
M24	435.0	380	28,000	4	-9.0	0.0	140	95
M25	981.0	785	>50,000	5	-2.1	0.0	165	135
M26	745.2	690	42,000	4	-6.4	0.0	280	110

3.2. Dimensional Stability, Torque Skewness, and Comfort Characterization

Laundering exposures emphasized the primary risk factors and dimensional instabilities of natural fibers. Specimen M2 (100% Cotton Single Jersey) exhibited severe structural contraction, reaching a critical -13.3% shrinkage along the courses (lengthwise) direction. This *büzülme* (dimensional contraction) stems directly from relaxation shrinkage, where mechanical viscoelastic strains frozen inside the loops during manufacturing unlock upon exposure to water. The moisture acts as a plasticizer, releasing the stored tension and forcing the distorted loops to revert to their thermodynamic equilibrium state.



Furthermore, M2 failed the industrial skewness criteria, displaying a spirality torque of 5.2%, while M3 reached an even higher 5.8%. Both samples exceeded the standard industrial performance ceiling of $\leq 5.0\%$. This twisting defect is driven by the residual torsional torque of the ringspun yarns, which causes loop tilt once the fabric is wetted. Conversely, Specimen M25 (Interlock) displayed robust geometric invariance, with negligible shrinkage values of -1.5% crosswise and -2.1% lengthwise. This superior stability is due to the structural symmetry of the interlock architecture; its back-to-back double-knit construction effectively counteracts internal mechanical stresses and neutralizes yarn torque, preventing both shrinkage and spirality.

3.3. Multi-Axial Elasticity and Environmental Fastness Records

Elastic extension profiles proved that knitting geometry dictates raw stretchability, but yarn composition controls elastic recovery. Material M14 (Cotton Rib) recorded a high crosswise extension of 122.5% under standard load, yet its recovery was highly inefficient, leaving a severe permanent deformation with only a 73.7% recovery rate. This poor recovery is due to the plastic deformation behavior of natural cotton fibers, which lack the molecular elasticity to overcome the structural displacement of the rib loops.

Conversely, Material M13 (Synthetic PES Rib) limited its elongation to 54.4% but showed an exceptional 99.0% elastic recovery rate, locking back perfectly to its original shape thanks to the high resilience and synthetic polymer memory of polyester. Additionally, fastness metrics across wash, rubbing, and sweat tracks showed stable Grade 4-5 performance for the synthetics, confirming that the synthetic fibers offer superior molecular stability against both mechanical and chemical degradation.

4. TECHNICAL IMPLEMENTATION MODEL (BODY MAPPING LAYOUT)

Synthesizing all 16 evaluation results, an optimal regional textile mapping for high-performance athletic wear is structured in Table 3.

Table 3: Optimal regional textile mapping for high-performance athletic wear

Anatomical Target Area	Selected Code	Fabric Architecture	Mass (gsm)	Raw Material Fiber Mix	Primary Engineering Rationale
Main Torso Core	M25	Interlock Knit	150	100% Polyester	981 N burst defense, high dimensional locking, optimal heat dissipation.
Collar & Cuffs	M13	Rib 1x1 Construction	255	100% Polyester	99% elastic shape recovery, contours smoothly without permanent sagging.
High-Sweat Aeration	M7	Open Mesh Filet	140	100% Recycled PES	High airflow, fast capillary sweat removal, ecodesign integration.



5. CONCLUSIONS

1. Pure natural cotton fibers fail active sportswear limits due to excessive washing contraction (-13.3%) and poor recovery kinetics (73.7%), regardless of their comfortable hand properties.
2. Double-knit synthetic geometries, specifically interlock structures, present superior structural security with a ball burst protection of 981.0 N and minimal shrinkage variations.
3. Recycled polyester configurations achieve mechanical and fastness parity compared to virgin synthetic paths, proving eco-friendly sportswear viability.
4. The implementation of body mapping, grouping interlock, high-elasticity ribs, and hyper-porous recycled mesh across specific biological layout regions, satisfies modern performance standards.

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