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Soft, wearable, microfluidic system for fluorometric analysis of loss of amino acids through eccrine sweat

This paper presents a soft, skin-interfaced microfluidic system for real-time amino acid analysis in eccrine sweat. Using integrated fluorometric assays and smartphone-based imaging, this cost-effective platform enables quantitative monitoring without the need for electrochemical sensors or batteries. Human subject studies investigate amino acid losses during exercise, highlighting the importance of sufficient recovery periods and dietary supplementation. This system offers potential applications in athletic and clinical settings, where maintaining amino acid balance is essential for homeostasis.

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Soft, wearable, microfluidic system for fluorometric analysis of loss of amino acids through eccrine sweat†

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Amino acids are essential for protein synthesis and metabolic processes in support of homeostatic balance and healthy body functions. This study quantitatively investigates eccrine sweat as a significant channel for loss of amino acids during exercise, to improve an understanding of amino acid turnover and to provide feedback to users on the need for supplement intake. The measurement platform consists of a soft, skin-interfaced microfluidic system for real-time analysis of amino acid content in eccrine sweat. This system relies on integrated fluorometric assays and smartphone-based imaging techniques for quantitative analysis, as a simple, cost-effective approach that does not require electrochemical sensors, electronics or batteries. Human subject studies reveal substantial amino acid losses in sweat from working muscle regions during prolonged physical activities, thereby motivating the need for dietary supplementation. The findings suggest potential applications in healthcare, particularly in athletic and clinical settings, where maintaining amino acid balance is critical for ensuring proper homeostasis.

Introduction

As the fundamental building blocks of proteins and as critical aspects of numerous metabolic processes, amino acids and their net balance in the body are essential for homeostasis and general health.[1] Amino acids undergo continuous turnover, primarily due to their role in the synthesis of proteins and other biomolecules and in energy metabolism.[2] Non-essential amino acids can be synthesized within the body for replenishment, while essential amino acids must be obtained from dietary intake.[3] Deficiencies in either type of amino acid can disrupt natural bodily functions, such as protein synthesis and tissue repair, and may lead to impaired metabolic processes and immune responses.[4,5] During prolonged periods of exercise, such as endurance training, eccrine sweat can become a significant channel of amino acid loss.[6] Physical exertion leads to elevated metabolic activity, resulting in increased amino acid concentrations in sweat.[7] Given that whole-body sweat loss rates can reach up to 2 liters per hour during exercise,[8] this loss mechanism may cause significant depletion of amino acids, thereby necessitating intake through supplements. Current methods for monitoring amino acid balance require analysis of blood and urine, involving procedures that are invasive and restricted to discrete sampling, typically performed in a hospital setting by trained personnel.[9]

Analysis of sweat is an attractive, alternative strategy for monitoring amino acid turnover owing to its ability for on-body, non-invasive collection and continuous sampling.[10] Past studies on the concentrations of amino acids in sweat reveal strong correlations with corresponding concentrations

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in blood.[6,11] Practical challenges with traditional methods for collection, however, prevent the capture of pristine samples of sweat without contamination from species on the surface of the skin.[12] Soft, skin-mounted microfluidic systems technologies overcome these and related limitations to enable contamination-free collection and continuous, quantitative analysis of biomarker concentrations in sweat.[13,14] When implemented with suitable electrochemical sensors, the result allows for measurements of concentrations of amino acids in sweat induced by iontophoretic delivery of pharmacological agents through the surface of the skin.[15] Studies with these systems reveal dynamic changes in amino acid concentrations, but without examining the role of sweat as a pathway for amino acid loss.

The work presented here leverages extended versions of soft, skin-interfaced microfluidic platforms, with target-specific fluorometric enzymatic assays for quantitative analysis in studies that address amino acid turnover and eccrine sweat as a loss channel for amino acids during exercise (Fig. 1a). This system bypasses the need for electrochemical sensors, supporting electronics and batteries, where quantitative results follow from image capture and analysis using a simple, smartphone-based imaging module.[16] Investigations involving human subjects provide insights into amino acid turnover, including the role of factors such as rate, gender difference, regions of working and non-working muscles, and sweat induction methods. Additional studies of sweat-facilitated amino acid loss and supplementation demonstrate the ability of this cost-effective system to track turnover, depletion, and restoration of amino acids, in a simple, practical manner that has potential for widespread, routine use.

Results and discussion

Device design

The system adopts a miniaturized, multi-layer structure formed in the elastomer polydimethylsiloxane (PDMS), with a

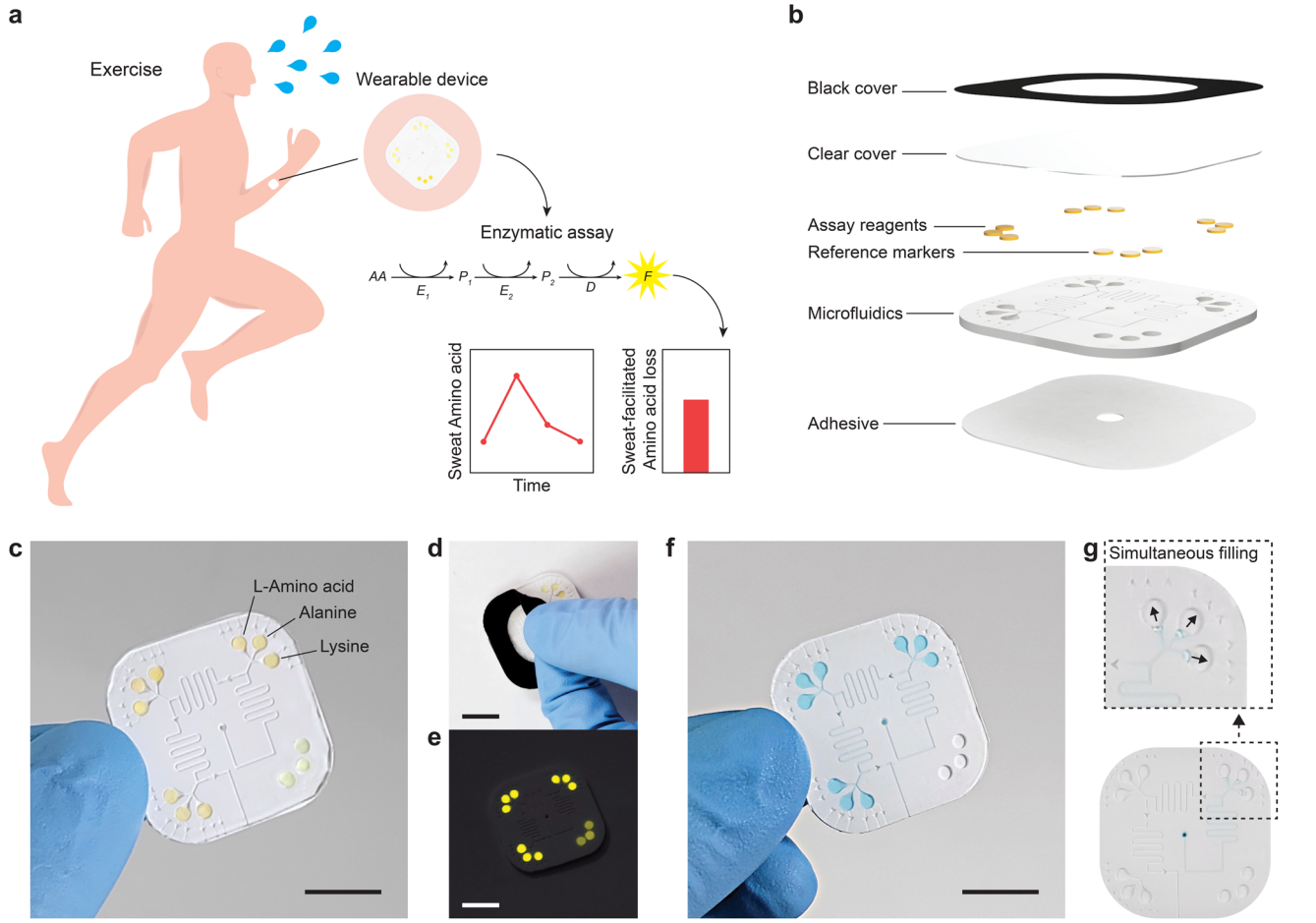

Fig. 1 Schematic illustrations and images of a soft microfluidic device for fluorometric measurements of amino acid concentrations in sweat. (a) Wearable device enables collection and analysis of sweat for enzymatic reaction and fluorometric monitoring of amino acids during exercise. (b) Exploded view illustration of a device designed for collection and fluorometric analysis of sweat collected into microreservoirs. (c) Three grouped reservoirs at each corner contain assays for total amino acid, alanine, and lysine, respectively. (d and e) A removable black cover protects the assays from ambient light, and after detachment enables fluorometric measurements. (f and g) The microfluidic system contains three sets of three grouped reservoirs. Capillary bursting valves ensure that each grouping fills simultaneously, and that the sets fill in a time-sequential manner. Scale bars, 1 cm.

thin geometry to enable a soft, water-tight bond to the surface of the skin without discomfort (Fig. 1b). An adhesive layer with an opening aligned to an inlet on the backside of the device allows sweat from a well-defined area on the skin to enter the system without leakage. The microfluidic network includes a central inlet, a collection of passive valves and interconnecting channels, three sets of grouped microreservoirs for simultaneous analysis of total amino acid, alanine (a non-essential amino acid), and lysine (an essential amino acid), and a set of outlets (Fig. 1c). Among the various amino acids found in sweat, alanine and lysine serve as specific target amino acids due to their distinct roles in metabolic activities, differentiated turnover behaviors, and unique side chain groups.[17] Details on the fabrication approaches and the designs appear in the Materials and methods section and ESI,† respectively. Each microreservoir contains enzymatic assay reagents for fluorometric measurements of the concentrations of specific amino acid species in sweat. Experimental results confirm that no statistically significant loss of amino acids occurs during transport of sweat samples through the PDMS microfluidics (Fig. S1†). A corona treatment process enables strong bonding between the skin adhesive, the microfluidic structure, and a clear cover layer. A removable black layer placed on top of the system protects the assay reagents from ambient light (Fig. 1d). These two cover layers, fabricated in PDMS, adhere to each other through van der Waals interactions, and thus can be easily removed after completion of the assay reaction. The device structure includes fluorescent reference markers fabricated by dispersing fluorescent dye particles in PDMS, to facilitate quantitative analysis (Fig. 1e). Quantitative analysis can be performed using a standard fluorescent imager in a dark room or using a smartphone-based imaging module including a miniature dark box and excitation filter (Fig. S2 and S3†). ESI† provides details on the smartphone-based imaging module.

The unique layout of the grouped microreservoirs enables collection and efficient multiplexed analysis of sweat for individual biomarkers (Fig. 1f). Sweat passes through a single inlet, into channels that include capillary bursting valves for sequential collection of triplicate sweat samples for analysis (Fig. S4 and Table S2†).[18] Experimental demonstrations with dyed fluids illustrate simultaneous filling of grouped microreservoirs (Fig. 1g and S5†), as further validated through computational fluid dynamics (CFD) simulations (Fig. S6†). ESI† provides details on the microfluidic design and CFD simulations.

Enzyme-based fluorometric assays of amino acids

In general, enzymatic assays react rapidly, sensitively, and selectively towards specific target species, thereby eliminating the need for purification of raw biological samples.[19] Unlike other fluids such as blood and urine, biomarker analysis in sweat relies on volumes in the microliter range and requires comparatively high levels of sensitivity. The schemes for sweat amino acid analysis featured here utilize coupled enzymatic assays, where a highly sensitive first reaction precedes a reaction with a strong fluorescent response (Fig. 2a).[20] Modified mixtures of buffer solution, enzymes, and fluorescent probes, which are detailed in the Materials and Methods section, based on kits originally designed for traditional biological fluids serve as assay reagents for analysis of sweat. The fluorescent probes have similar excitation and emission wavelengths (E_x/E_m = 535/587 nm for total amino acid, E_x/E_m = 535/587 nm for alanine, and E_x/E_m = 538/587 nm for lysine) to enable analysis of all three biomarkers in a single measurement. Drop-casting and vacuum drying procedures deliver these assay reagents to filter paper cut-outs coated with a layer of the hydrophilic polymer polyvinyl alcohol (PVA) to ensure effective wetting upon interaction with sweat.

Evaluations of the assays across physiologically relevant ranges use solutions prepared with known concentrations of amino acids in samples of artificial sweat that contain all of the major constituents in actual sweat, as described in the Materials and methods section.[21] The assays show excellent stability against potential interfering species, including urea, lactate, Ca^{2+}, Mg^{2+}, uric acid, glucose, and other amino acids[22] (Fig. S6 and S7†). Normalized fluorescence intensities measured from standard solutions at physiological pH and temperature (6 and 36 °C, respectively) show a linear increase with increasing concentrations of total amino acid (coefficient of determination, R^2 = 0.987), alanine (0.996) and lysine (0.994) (Fig. 2b–d). Fluorescent images of the microreservoirs also demonstrate a similar, clear increase in fluorescence intensity. Each of the assays shows a high sensitivity (1.14×10^3 AFU mM^{-1} for total amino acid, 6.69×10^3 AFU mM^{-1} for alanine, and 1.24×10^4 AFU mM^{-1} for lysine) and a low limit of detection (LOD) (3.68 μM for total amino acid, 0.49 μM for alanine, and 0.13 μM for lysine) compared to recent wearable technologies (Table S1†). These assays operate over a range of concentrations (0–60 mM for total amino acid, 0–8 mM for alanine, and 0–3 mM for lysine) that are significantly larger than those for sweat from healthy individuals (6–10 mM for total amino acid, 0.3–1.5 mM for alanine, and 0.1–1 mM for lysine).[23] Fluorescence signals measured in 5 min intervals for 60 min show stabilization within <20 min, consistent with completion of the enzymatic reactions in this timeframe (Fig. S8†). Additional experiments indicate that the responses are nearly independent (<5% change in sensitivity) of pH and temperature for values between 4.5 and 9.0, and 30 and 38 °C, respectively (Fig. S9†). Degradation of the assays occurs for temperatures >40 °C, which is above the maximum skin temperatures observed during exercise, likely due to denaturing of the enzymes (Fig. S10 and S11†).[24] The assays can be preserved for up to 12 weeks under storage conditions of −18 °C and up to two weeks at room temperature (Fig. S12†).

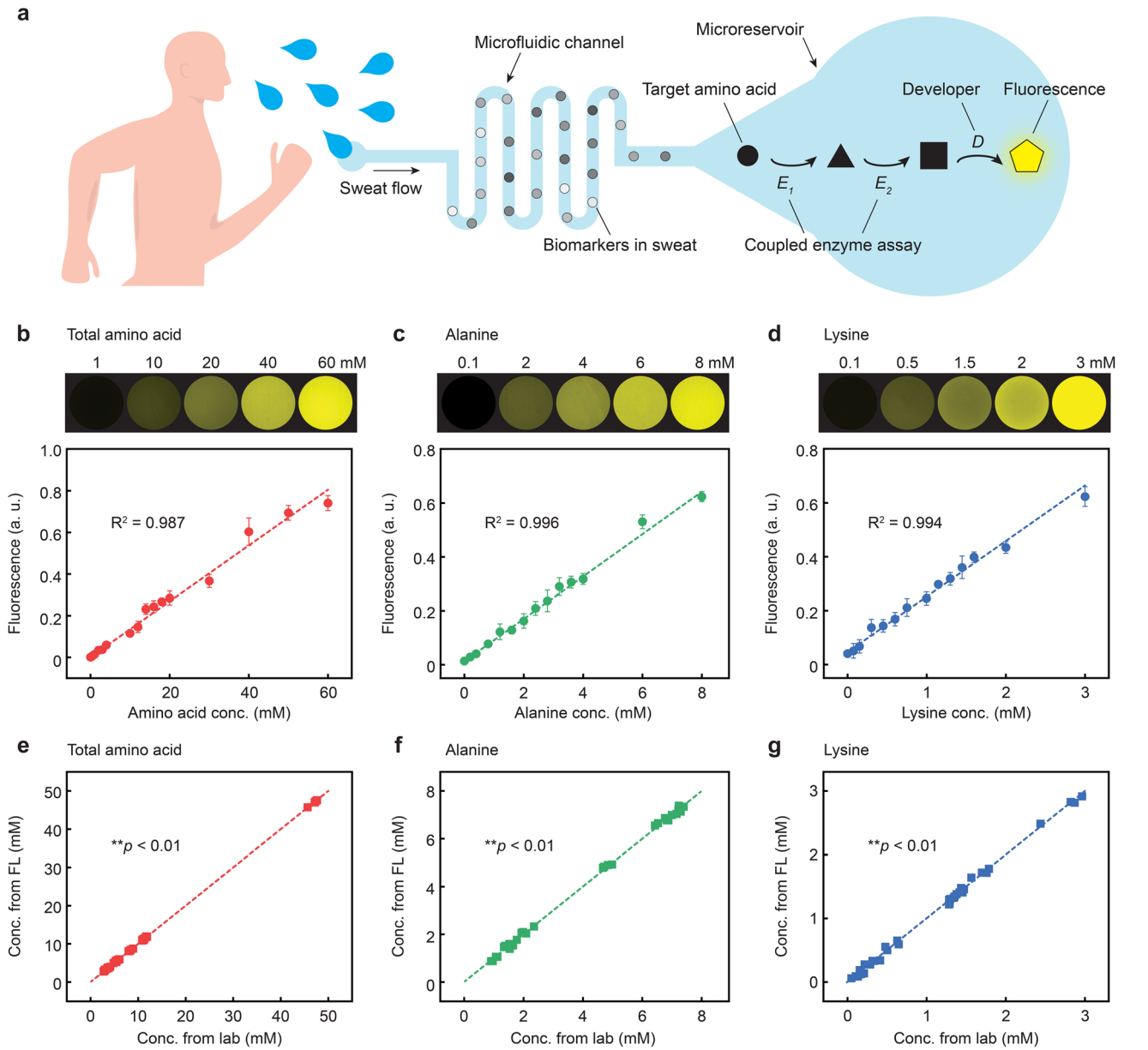

Fig. 2 Fluorometric analysis of amino acid concentrations in sweat based on enzymatic assays. (a) Schematic illustration of chained enzymatic reactions designed for highly selective fluorometric detection of specific amino acid species. Fluorescence images and standard curves for total amino acid (b), alanine (c), and lysine (d) showing fluorescence as a function of concentration. Fluorometric results and those obtained by NMR for total amino acid (e), alanine (f), and lysine (g) (n = 8).

Further validation involves comparisons of results from on-body tests using the devices to those obtained from sweat collected with absorbent pads and subsequently analyzed by nuclear magnetic resonance (NMR). The studies include five different regions of the body (forehead, chest, lower back, forearm, and thigh) and eight subjects (4 male and 4 female). The results are in excellent agreement, with Pearson coefficients of >0.99 and low two-tailed p values of $^{**}p < 0.01$ for total amino acid, alanine, and lysine (Fig. 2e–g). In addition, amino acid concentrations in sweat measured using the enzymatic assays correlate well with those in blood measured through NMR (Fig. S13†).

Analysis of sweat amino acid concentrations during exercise

These systems can continuously track amino acid turnover, as guidance for consumption of supplements to replenish loss without the need for blood testing. Human subject studies to demonstrate these capabilities examine sweat amino acid concentrations before, during, and after a 90 min exercise on a stationary bike (Fig. 3a), from working (thigh) and non-working (forearm) regions of the body (Fig. 3d–f). Before exercise, levels from the working and non-working regions are similar (7.9 and 8.2 mM for total amino acid, 1.0 and 1.0 mM for alanine, and 0.24 and 0.28 mM for lysine).

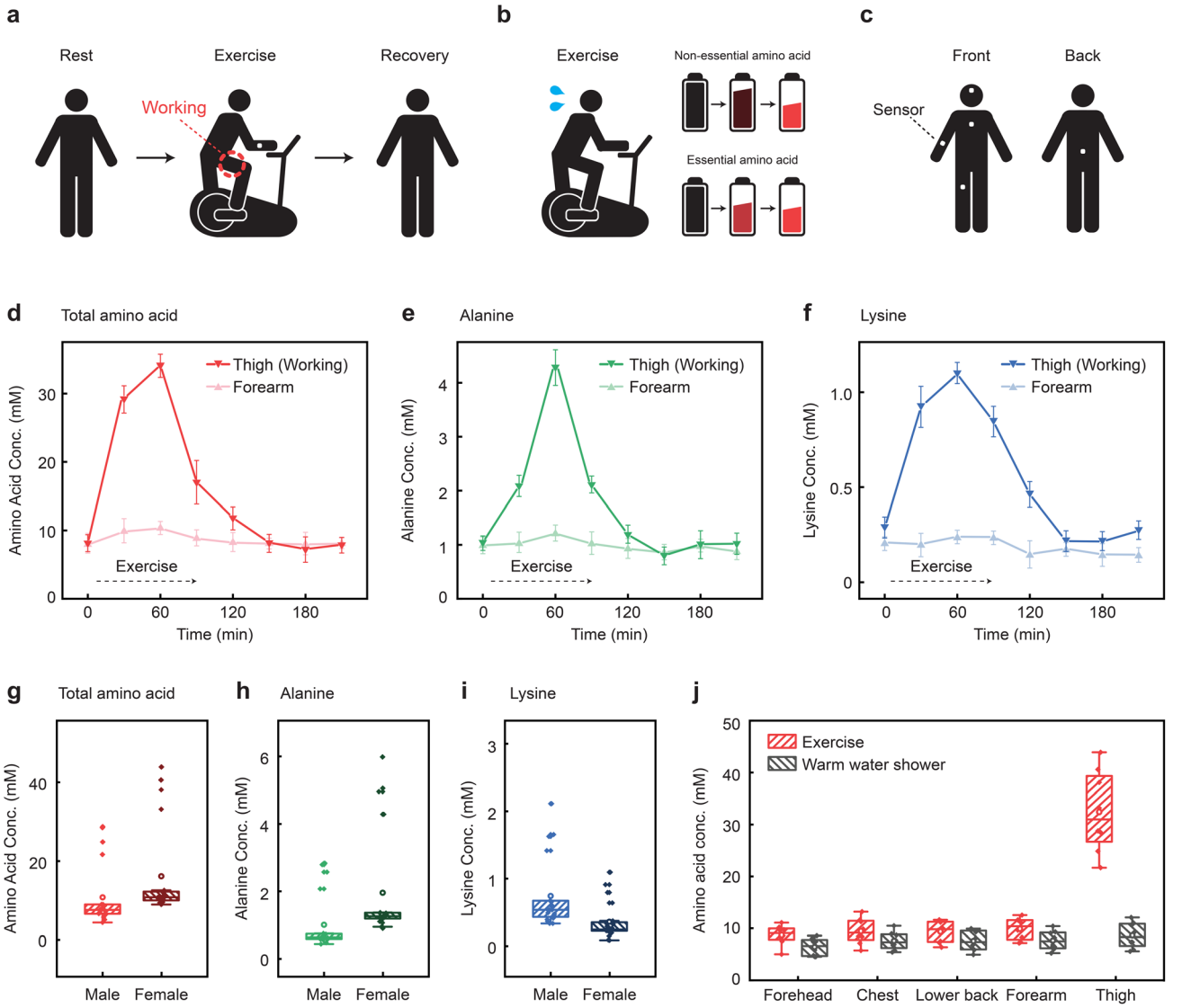

Fig. 3 Evaluation of the concentrations of amino acids in sweat. (a) Protocol for human subject studies involving exercise on a stationary bike. (b) Illustration of the variation in turnover rates for non-essential and essential amino acids during exercise. (c) Five regions of the body selected for sweat collection. (d–f) Time-dynamic analysis of total amino acid (d), alanine (e), and lysine (f) in sweat before, during, and after exercise from a working region (thigh) and non-working region (forearm). (g–i) Box and whisker plot of the concentrations of total amino acid (g), alanine (h), and lysine (i) in sweat for male and female subjects after exercise from non-working regions (box and whiskers) and working regions (outliers). (j) Box and whisker plot of the concentration of L-amino acid in sweat after exercise and a warm water shower from five regions of the body (n = 8).

During exercise, amino acid concentrations from working regions increase by ≈300% (34.1 mM for total amino acid, 4.3 mM for alanine, and 1.2 mM for lysine after 60 min of exercise), while those from non-working regions increase by only ≈20% (10.3 mM for total amino acid, 1.2 mM for alanine, 0.24 mM for lysine). These results align with expected increases in protein breakdown, blood flow, and metabolism in working regions.[25] Different amino acids show different behaviors (Fig. 3b). While alanine, a non-essential amino acid, shows a delayed steep increase 30 min into the exercise (Fig. 3e), lysine, an essential amino acid, shows a sharp initial increase (Fig. 3f). Such trends can be explained by the different turnover rates of amino acids and the reflection of these changes in their concentrations in sweat.[26] Non-essential amino acids, with lower turnover rates owing to adjustable synthesis rates, show a delayed change in concentration. By contrast, essential amino acids, with higher turnover rates due to their involvement in more crucial metabolic processes, show a comparatively rapid change. As a control, experiments on sweat induced by methods other than exercise, such as warm water shower and iontophoretic delivery of pilocarpine, show no significant differences in amino acid concentrations before, during, and after induction, from the thigh and forearm (Fig. S14†).

Further studies explore the dependence of sweat amino acid concentrations on gender and body location through experiments performed 60 min into exercise from five different regions of the body (forehead, chest, lower back,

forearm, and thigh) (Fig. 3c) of eight subjects (4 male and 4 female). The selected locations follow regional models developed to represent the whole body.[27] The results indicate that female subjects have higher levels of total amino acid and alanine, while male subjects have higher levels of lysine. These differences likely follow from hormonal variations that regulate metabolic activity, as reported in studies on physiology (Fig. 3f–h).[28] Unlike amino acid concentrations observed in sweat induced by a warm water shower, exercise-induced sweat shows a strong dependence on location. The four non-working regions (forehead, chest, lower back, forearm) show relatively similar levels of amino acid (22% standard deviation), significantly lower than those in working regions (thigh; ≈300% of non-working regions) (Fig. 3j).

Studies of sweat-facilitated loss of amino acids

As mentioned previously, this system can monitor sweat-facilitated loss of amino acids. The rate of whole-body sweat loss during exercise can exceed 2 liters per hour, requiring proper hydration to avoid adverse consequences. Excessive sweating can also cause rapid turnover of certain metabolites

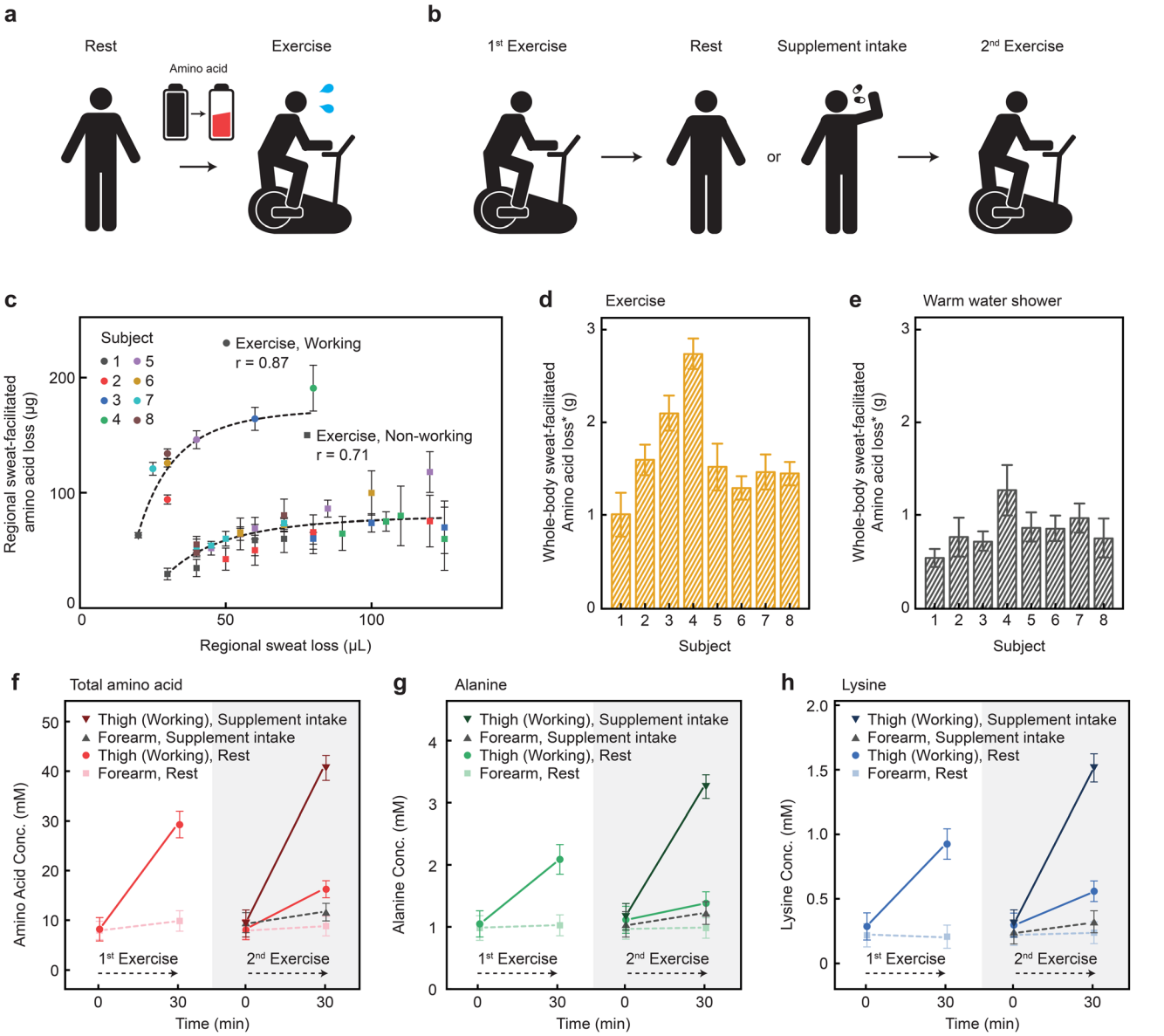

Fig. 4 Sweat-facilitated loss of amino acids during exercise and effects of supplement intake. (a) Illustration of amino acid loss associated with sweating induced by exercising on a stationary bike. (b) Protocol for human subject studies comparing two recovery methods, one that involves only rest and the other that involves rest and supplement intake, between two exercise sessions. (c) Correlation of total amino acid loss and total sweat loss after exercise from working and non-working regions (n = 8). Estimated whole-body amino acid loss from exercise (d) and a warm water shower (e) (n = 8). (f–h) Sweat amino acid levels from a working region (thigh) and non-working region (forearm) during two consecutive exercise sessions comparing the same to recovery methods mentioned previously, for total amino acid (f), alanine (g), and lysine (h).

that appear in sweat. For amino acids, substantial decreases in net balance in the body can be induced by exercise (Fig. 4a).

Analysis for various regions of the body indicates that regional amino acid loss increases with regional sweat loss (Pearson coefficient of 0.87 for working regions during exercise, 0.71 for non-working regions during exercise, and 0.77 for all regions after a warm water shower) (Fig. 4c and S15†). Based on data collected 30 min into exercise or warm water shower from five regions of the body, whole-body sweat loss and whole-body amino acid loss can be estimated using previously established relations between regional and whole-body sweat.[29] While whole-body sweat loss estimates for exercise (1.04 ± 0.50 L) and warm water shower display similar levels (1.09 ± 0.49 L) (Fig. S16†), estimates of whole-body amino acid loss from exercise (1.65 ± 0.50 g) are considerably higher levels than those from warm water shower (0.85 ± 0.20 g) (Fig. 4d and e). Given that 100–200 g of total free amino acids circulate in the human body[30] and the average basal amino acid turnover rates of 0.8 g per hour,[26] sweat-facilitated amino acid loss of >2 g per hour can be significant during exercise, thereby requiring supplementation.

Further insights on amino acid turnover follow from studies to compare the effect of oral supplement intake for replenishment after exercise.[31] The experiments involve monitoring sweat amino acid concentrations during two consecutive 30 min exercise sessions on a stationary bike, separated by a 1 hour recovery period either for rest or oral supplement intake (Fig. 4b). Comparisons of amino acid concentrations in sweat during the first and second exercise sessions reveal distinct patterns based on the recovery method (Fig. 4f–h). For the case of resting during the recovery period, sweat amino acid concentrations significantly decrease for both working (by 44.5% for total amino acid, 33.9% for alanine, 39.7% for lysine) and non-working regions (by 10.5% for total amino acid 4.1% for alanine, 3.8% for lysine). These results indicate insufficient recovery from turnover of amino acids caused during the first exercise session. Additional studies suggest that an extended 4 hour recovery period facilitates meaningful replenishment of non-essential amino acids (Fig. S17†). For the case of oral supplement intake during the recovery period, sweat amino acid concentrations substantially increase for both working (by 39.6% for total amino acid, 57.0% for alanine, 64.6% for lysine) and non-working regions (by 16.2% for total amino acid, 17.5% for alanine, 56.4% for lysine). These findings suggest that proper supplementation can sufficiently replenish amino acids and address potential health risks arising from turnover.

Conclusions

The findings reported in this work highlight the significance of eccrine sweat as a pathway for amino acid loss during exercise. The soft, microfluidic, wearable systems and fluorometric analysis approaches introduced here enable accurate, non-invasive, real-time chemical analysis of sweat in a simple, cost-effective manner that suggests a potential for widespread, routine use (Table S3†). Results from human trials involving exercise reveal substantial amino acid turnover, especially in working muscle regions, thereby validating the importance of continuous monitoring of amino acid homeostasis during exercise. Additional studies provide further insight into differences in metabolic response depending on gender, regions of the body, and supplementation. This research advances an understanding of amino acid turnover during exercise, particularly in the context of excessive sweating, and offers a practical solution for management. Future work may be directed toward overcoming limitations of the current system, which include the irreversible, and thus non-reusable, nature of the assays and their sensitivity to operating and storage temperatures outside of a relatively narrow range.

Materials and methods

Preparation of the enzymatic assay

Commercially available reagents were used to prepare the enzymatic assays for total amino acid (L-amino acid assay kit, ab65437, Abcam, UK), alanine (L-alanine assay kit, ab83394, Abcam, UK), and lysine (lysine assay kit, ab273311, Abcam, UK). For the total amino acid assay, 7.5 μl of the enzyme diluted in 220 μl assay buffer solution and 7.5 μl of the probe were mixed with 35 μl assay buffer solution to yield a 50 μl reaction mix. For the alanine assay, 5 μl of the converting enzyme diluted in 220 μl assay buffer solution, 5 μl of the development enzyme diluted in 220 μl assay buffer solution, and 5 μl of the probe were mixed with 35 μl assay buffer solution to yield a 50 μl reaction mix. For the lysine assay, 6 μl of the converting enzyme diluted in 220 μl assay buffer solution, 6 μl of the development enzyme diluted in 220 μl assay buffer solution, and 3 μl of the probe were mixed with 35 μl assay buffer solution to yield a 50 μl reaction mix.

Fabrication and assembly of microfluidic system

3D printing formed molds with corresponding microfluidic features of relief. A mixture of 5 wt% white dye (Reynolds Advanced Material, IL, USA) and PDMS prepolymer (Sylgard 184, mixing ratio 10 : 1, Dow Corning, MI, USA) was poured into the mold and leveled using a razor blade. Degassing and thermally curing at 70 °C for 3 h yielded a solid elastomeric element. After removal from the mold, a mechanical punch tool defined the inlet. Circular cellulose paper (Whatman, MA, USA) cutouts formed using a CO_2 laser (VLS, Universal Laser Systems, AZ, USA) were coated with PVA (Sigma-Aldrich, MO, USA) by drop-casting and vacuum drying 2 μl of a 1 wt% PVA solution in deionized water. 2 μl of enzymatic assay reaction mix was then drop-cast and vacuum dried onto the PVA-coated cellulose paper cutouts and then placed in the microreservoirs. Reference markers were formed by mixing fluorescent pigment (Reynolds Advanced Material, IL, USA) with PDMS prepolymer. A thin clear cover layer was formed by spin casting PDMS prepolymer and thermal curing at 70 °C for 1 h. A black cover layer was formed on 3D printed

mold with a mixture of 5 wt% black dye (Reynolds Advanced Material, IL, USA) and PDMS prepolymer. Assembly of the device involved corona treatment to enable bonding of each PDMS layer and a medical-grade adhesive (1524 skin adhesive, 3M).

Artificial sweat

Artificial sweat solution was prepared by mixing 22 mM urea (Sigma-Aldrich, MO, USA), 5.5 mM lactate, 3 mM NH^{4+} (NH_4-Cl, Sigma-Aldrich, MO, USA), 0.4 mM Ca^{2+} ($CaCl_2$, Sigma-Aldrich, MO, USA), 50 μM Mg^{2+} ($MgCl_2$, Sigma-Aldrich, MO, USA), 25 μM uric acid (Sigma-Aldrich, MO, USA), and 0.1 mM glucose (Sigma-Aldrich, MO, USA) in deionized water, according to previously reported procedures.

Characterization

The main paragraph text follows directly on here. Calibration of the fluorometric system was based on fluorescence measured by the Azure Sapphire™ Biomolecular Imager and NMR measured by the X500 Bruker Avance III HD system.

Human subject studies

Human subject studies were approved by the Institutional Review Board (STU00214004-MOD0023) Office at Northwestern University and all subjects provided complete, informed, signed consent.

Blood sampling

After alcohol sanitization, a commercially available lancing device (21G thickness, 1.8 mm length) punctured the finger to draw blood samples. Gentle pressure around the puncture site allowed a small drop of blood to form, which was collected using a 15 μL capillary blood collection tube (PTS Diagnostics Inc, IN, USA). More than 40 μL blood samples were collected in the LoBind Eppendorf tubes to extract sufficient volumes of serum. Resting the collected blood samples for 45 minutes at room temperature induced blood clotting for subsequent serum separation. Centrifugation at 4000 rpm for 15 minutes separated serum from clotted blood cells, and a micropipette aspirated the separated serum from the tube. The second centrifuge at 4000 rpm for 1 minute further purified the collected serum sample. After extracting the serum, sample volumes were adjusted to 500 μl by diluting with deuterium oxide (D_2O) for NMR analysis.

Sweat collection

The skin of the collection area was cleaned with an alcohol pad prior to attachment of the microfluidic system. For non-exercise sweat induction methods such as rest before exercise, recovery 30 min past the end of exercise, and warm water shower, pilocarpine-based iontophoresis stimulation was used. Microfluidics were single-use for each measurement.

Regional and whole-body calculations

Regional sweat loss was measured by the total volume of sweat collected from a specific region of the body. Regional sweat-facilitated amino acid loss was calculated using the average amino acid concentrations and the total volume of sweat collected from a specific region of the body. Whole-body sweat loss and whole-body sweat-facilitated amino acid loss were calculated from the aggregates of regional sweat loss and regional sweat-facilitated amino acid loss, respectively, from all five regions of the body (forehead, chest, lower back, forearm, and thigh), which were weighted for regional body surface area using the weighting coefficients shown in Table S4.† Body surface area was calculated from height and body mass.[32]

Data availability

Human subject data used in this study are not publicly available to protect the identity of participants according to the Northwestern University Institutional Review Board (IRB). Data for this article are available at Dryad at **https://doi.org/10.5061/dryad.95x69p8v0**.

Author contributions

S. H. C. and S. C. contributed equally to this work. S. H. C.: conceptualization, methodology, experiments, characterization, formal analysis, investigation, data curation, visualization, writing; S. C.: methodology, experiments, characterization; Z. L.: validation, writing; Y. S.: conceptualization, characterization; S. L.: methodology, experiments; M. Z., R. F. N., E. E. K.: experiments, characterization; R. G.: methodology, resources; D. K.: supervision, resources; Y. H.: project administration, supervision; J. A. R.: funding acquisition, project administration, supervision, writing – review and editing.

Conflicts of interest

R. G. and J. A. R. are co-founders of a company, Epicore Biosystems, that develops and commercializes microfluidic devices for sweat analysis.

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