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Impact of Custom Features of Do-it-yourself Artificial Pancreas Systems (DIYAPS) on Glycemic Outcomes of People with Type 1 Diabetes

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***Abstract*— One of the benefits of Do-it-yourself Artificial Pancreas Systems (DIYAPS) over commercially available systems is the high degree of customization possible through various features developed by the community. This paper investigates the impact of thirteen commonly used custom features on the glycemic outcomes of users with type 1 diabetes. Significant differences were observed in the group using the Automated Microbolus, Autotune (automatic), and the Superbolus feature. As many of the features aim to improve not only glycemic outcomes but also reduce the burden of managing diabetes on the user, future studies should investigate the impact of these features on the quality of life of their users.**

***Clinical Relevance*—This paper expands the existing knowledge on the DIYAPS for people with type 1 diabetes which have been gaining popularity among the patient population in recent years.**

I. INTRODUCTION

The improvement in accuracy and availability of diabetes technology such as continuous glucose monitors (CGMs) has allowed for automation of some aspects of diabetes management [1], [2]. The integration of CGMs with insulin pumps has allowed the creation of hybrid closed-loop systems, i.e., algorithms to regulate basal insulin levels to keep glucose at a target level [1]. Nevertheless, such commercially available systems have limited affordability, accessibility and take a long time to develop [3]. The frustration of the community with these limitations has created the patient-driven #WeAreNotWaiting movement[1] [4], [5]. One of the outcomes of this movement was the creation of Do-it-yourself Artificial Pancreas Systems (DIYAPS), which involves the "hacking" of commercially available devices such as insulin pumps and CGMs and utilizes microcomputers or smartphones to run custom open-source algorithms, resulting in better accessibility of artificial pancreas systems [6]. The OPEN Project (Outcomes of Patients' Evidence With Novel, Do-It-Yourself Artificial Pancreas Technology) is an EU-sponsored project investigating the use of DIYAPS in a real-world setting[2] [3].

Another advantage of using DIYAPS is the availability of a large variety of custom features and personalization options the user can choose from [6]. These features aim to address some of the challenges associated with diabetes management, such as achieving stable blood glucose levels or reducing the burden of the condition on the user. This paper investigates whether several custom features of three popular DIYAPS systems (OpenAPS[3], AndroidAPS[4], and Loop (iOS)[5]) have an impact on the glycemic outcomes and diabetes management of their users. This paper first describes the outcome metrics used in diabetes management, which are then used to determine whether the use of various features leads to better outcomes, and the results are presented.

II. BACKGROUND

Type 1 diabetes (T1D) is an autoimmune condition caused by the immune destruction of pancreatic insulin-producing beta cells [7]. As insulin is the only glucose-lowering hormone in the human body, T1D results in chronic hyperglycemia (>180 mg/dL), and people with diabetes (PwD) rely on a lifelong administration of exogenous insulin [8]. Therefore, the treatment goals for T1D focus on keeping glucose levels as close to those of individuals without diabetes while also avoiding hypoglycemia (<70 mg/dL) [9].

Achieving glycemic outcomes within the optimal range helps to avoid acute complications such as severe hypoglycemia or diabetic ketoacidosis [8] as well as reduce the risk of long-term complications [11]. The current gold standard for assessing glycemic outcomes is the measurement of glycated hemoglobin (HbA1c) [12], [13]. However, the widespread use of CGMs has allowed the definition of additional diabetes management metrics which do not require a laboratory test [14]. As the HbA1c value reflects the retrospective long-term mean blood glucose value, the mean sensor glucose value recorded continuously by the CGM is a relevant factor in diabetes management [14]. Furthermore, several papers propose a function of the mean sensor glucose value to estimate the HbA1c based on the mean blood glucose, i.e., the estimated HbA1c (eHbA1c) or the Glucose Management Indicator (GMI) [15], [16]. Time in range (TIR), the time below the range, and time above the range are other key indicators of diabetes management as they provide more information about the day-to-day glycemic excursions [9], [14], [17], [18]. Other studies have also pointed to glucose variability as a more meaningful indicator for long-term complications and mortality than the mean glucose level, resulting in the definition of the coefficient of variation (CoV) of sensor glucose as an essential metric [19].

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[2]https://open-diabetes.eu/
[3]https://openaps.org/
[4]https://androidaps.readthedocs.io/
[5]https://loopkit.github.io/loopdocs/

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The American Diabetes Association (ADA) recommends an HbA1c of <7% / 53 mmol/mol for most adults with T1D [9], and lower targets should only be set if hypoglycemia can be avoided [10]. Studies showing the relationship between mean sensor glucose and HbA1c recommend mean sensor glucose of 154 mg/dL to achieve the HbA1c value of 7% [20]. For the majority of PwD, the TIR of 70% is recommended [18]. It is also noted that every further 5% increase in TIR has a clinically relevant impact on reducing the risk of long-term complications [17]. Time below 70 mg/dL should not exceed 4%, of which only 1% should be below 54 mg/dL. Time above 180 mg/dL should be below 25%, of which only 5% should be above 250 mg/dL. The CoV should be $\leq$ 36% [9], [19]. Furthermore, the medical community recognizes the trade-off between stringent care to achieve optimal care and the burden of diabetes management on the PwD, and considers the satisfaction of the PwD with their treatment a vital treatment goal [21], [22].

Despite advances in diabetes technology, only 21% of adults and 17% of youth achieve optimal glycemic outcomes [23], [24]. Previous studies have demonstrated the effectiveness of DIYAPS in reducing HbA1c values and time in hypoglycemia, as well as increasing time in range [25], [26], [27]. Benefits of DIYAPS span beyond just improved clinical outcomes. One of the benefits of DIYAPS is the high level of customization and features that the user can enable. While the value of DIYAPS has been demonstrated, there is limited research into the settings of these systems which lead to the best outcomes.

III. MATERIALS AND METHODS

A. Materials

The DIYAPS consists of a CGM, an insulin pump, and a minicomputer or smartphone app. Depending on their smartphone device, users can choose between three systems: AndroidAPS, Loop (iOS), or OpenAPS running on an extra minicomputer (e.g. Raspberry Pi). These three components form a control loop that aims to keep the users' glucose levels at a target level by continuously providing the required insulin as calculated by the algorithm based on the CGM data. The OPEN Project regularly collects data from users of DIYAPS through online campaigns. Participants are also invited to participate in surveys about their demographics, clinical outcomes, and quality of life. The cohort consists of 74 users and includes adults (n = 66), and children and adolescents (n = 8), with the age range of 5 to 78. 41% of the participants were female (n = 30), 59% were male (n = 44). The mean age at diagnosis was 14.1 years (sd = 8.4 years), and the mean years lived with diabetes was 24 years (sd = 13.1 years). All of the 74 users have reported the use of at least one custom feature, and 70% of users have reported the use of at least three features.

B. Methods

Based on the outcome metrics prioritized by the ADA, nine metrics were chosen to assess the level of diabetes management. Eight of the metrics were calculated based on the donated CGM data of the users: sensor glucose, coefficient of variation of blood glucose, glucose management indicator (GMI), time in range (70-180 mg/dL), time below 70 mg/dL (mild hypoglycemia), time below 54 mg/dL (severe hypoglycemia), time above 180 mg/dL (mild hyperglycemia), time above 250 mg/dL (severe hyperglycemia). The ninth metric was the self-reported most recent HbA1c value, which was taken from the survey.

The distribution of each metric was checked using the Shapiro-Wilk test to establish which significance test to use. The coefficient of variation and the most recent HbA1c value were the metrics that followed a normal distribution. Therefore for these metrics, the analysis of variance test (ANOVA) was used. For the other metrics, the non-parametric Kruskal-Wallis test was used. This test was chosen as it allows for small sample sizes ($\geq$ 5). In this paper, "users" refers to the participants who have stated that they use this particular feature, while "non-users" refers to participants who do not use the feature. The number of users for each feature and the availability of the features across the three systems are presented in Table I. The significance test was then performed to establish whether there was any difference between the outcomes of the "user" group compared with the "non-user" group. As significance level we chose $\alpha = 0.05$. As most of the metrics used in this paper do not follow the normal distribution, all significant findings are reported as the median value, followed by the range of values.

IV. RESULTS

Across the nine outcome metrics, no significant differences were observed between users and non-users of the features Temporary Targets, Profile Switches, Super Micro Bolus, Unannounced Meals, Automation, Autosens, Remote Follower, Autotune (manual), Manual Overrides, and Autobolus. The three features, Automated Microbolus, Autotune (automatic), and Superbolus, have shown a significant difference in outcomes of users of the features versus non-users for at least one of the outcome metrics and are summarized in Tables II, III and IV, respectively.

V. DISCUSSION

The management of T1D is a daily burden that heavily affects the quality of life of the PwD. Diabetes technology, such as DIYAPS, is crucial to achieving optimal blood glucose levels, as 95% of diabetes management is done by the person with diabetes [22]. The large variety of features available for DIYAPS allow the user to customize the system according to their body's needs and their individual preferences. While users of these systems can ask for advice in online communities, no previous studies have looked at the outcomes of users using different features. The study examines thirteen custom features available across the three DIYAPS (OpenAPS, AndroidAPS and Loop (iOS)). Significant differences were found for three of the thirteen features: Automated Microbolus, Autotune (automatic) and the Superbolus.

TABLE I

OVERVIEW OF THE 13 CUSTOM FEATURES INVESTIGATED, INCLUDING THEIR USE AND AVAILABILITY ACROSS THE THREE SYSTEMS

Feature	Number of users (% of cohort)	DIYAPS Availability	Feature Description
Remote Follower	40 (54%)	AndroidAPS, OpenAPS, Loop (iOS)	Allows the caregiver of the DIYAPS user to remotely monitor the glucose and insulin levels of the user through an app
Autotune manual	38 (51%)	AndroidAPS, OpenAPS, Loop (iOS)	Adjusts basal rates, insulin sensitivity ratios and carbohydrate ratios whenever triggered by the user
Temporary Targets	54 (73%)	AndroidAPS, OpenAPS	Change the target blood glucose level for a specified period of time e.g. a higher target during physical exercise
Profile Switches	33 (45%)	AndroidAPS, OpenAPS	Allows the creation of multiple insulin configurations (”profiles”) for various occasions, e.g. weekday, weekend, exam period etc.
Super Micro Bolus	50 (68%)	AndroidAPS, OpenAPS	Tiny amounts of bolus administered before a meal, combined with reduced basal insulin after a meal to better match the mealtime peak insulin timings
Unannounced Meals	43 (58%)	AndroidAPS, OpenAPS	Aims to detect rapid increases in blood glucose levels due to intake of carbohydrates and automatically correcting it
Automation	27 (36%)	AndroidAPS, OpenAPS	Automating the change of settings based on specified if statements e.g. if my location is detected to be at the gym, set my target to higher
Autosens	44 (59%)	AndroidAPS, OpenAPS	Adjusts the insulin sensitivity ratio in real time, if it detects that a user is reacting reacting more or less sensitively to insulin than usual
Manual Overrides	21 (28%)	Loop (iOS)	Allows the user to temporarily change their insulin requirements as a percentage, for basal rates and for boluses
Autobolus	5 (7%)	Loop (iOS)	A preset bolus dose to be administered at a particular time
Automated Microbolus	11 (15%)	Loop (iOS)	Small amounts of correction bolus administered to supplement the basal rate
Autotune automatic	6 (8%)	OpenAPS	Automatically adjusts basal rates, insulin sensitivity ratios and carbohydrate ratios over time
Superbolus	15 (20%)	AndroidAPS	A method of administering meal boluses which accounts for the carbohydrate content of the meal as well as the basal rate for the hours after the meal in order to reduce spikes in glucose levels

TABLE II

DIFFERENCES IN THE OUTCOMES OF USERS OF AUTOMATED MICROBOLUS VERSUS NON-USERS

Outcome Metric	p-value	Users (median (range))	Non-users (median (range))
Mean Sensor Glucose (mg/dL)	0.0231	121.75 (101.65-147.6)	137.05 (102.97-206.65)
Glucose Management Indicator (%)	0.0231	6.22 (5.74-6.84)	6.59 (5.77-8.26)
Time spent below 70 mg/dL (%)	0.0395	3.61 (2.24-13.84)	2.88 (0.07-9.12)
Time spent above 180 mg/dL (%)	0.0167	9.63 (1.33-24.0)	16.65 (0.83-70.48)
Time spent above 250 mg/dL (%)	0.0381	0.75 (0.03-4.9)	2.82 (0.01-21.9)

TABLE III

DIFFERENCES IN THE OUTCOMES OF USERS OF AUTOTUNE (AUTOMATIC) VERSUS NON-USERS

Outcome Metric	p-value	Users (median (range))	Non-users (median (range))
Most recent HbA1c reading (mmol/mol)	0.0059	67.5 62.0-74.0	58.0 36.0-75.0

TABLE IV

DIFFERENCES IN THE OUTCOMES OF USERS OF SUPERBOLUS VERSUS NON-USERS

Outcome Metric	p-value	Users (median (range))	Non-users (median (range))
Coefficient of Variation (%)	0.0457	37.4 (23.54-51.51)	33.62 (22.64-43.84)
Time below 70 mg/dL (%)	0.0035	6.42 (1.41-9.12)	2.81 (0.07-13.84)
Time below 54 mg/dL (%)	0.0027	1.07 (0.14-3.56)	0.43 (0.01-3.58)

a) Automated Microbolus on Loop (iOS): The users of the automated microbolus feature experienced lower mean glucose and GMI, lower time in hyperglycemia (time above 180 mg/dL and time above 250mg/dL) but at the expense of increased time below 70 mg/dL. The ADA guidelines state that lower mean sensor glucose can lead to a smaller risk for microvascular complications. It is, however, important to note that both groups fall in the advised range. Furthermore, the ADA recommends lower average glucose values only if it does not increase the risk of hypoglycemia [10]. This study has shown that the users of the Automated Microbolus feature do achieve lower mean sensor glucose, but the time spent in hypoglycemia is significantly higher than that of non-users of this feature.

b) Autotune (automatic) on OpenAPS: While there were no significant differences in the outcome metrics calculated based on the donated sensor data, there was a significant difference in the self-reported most recent HbA1c value. The users' HbA1c level lies above the ADA recommended level ($<$ 53 mmol/mol). However, it is important to note that only six users reported the use of this feature.

c) Superbolus on AndroidAPS: This study shows that the use of the Superbolus feature increased the glucose variability of the user, as well as their time in hypoglycemia, beyond the guidelines recommended by the ADA.

A. Limitations and Future Work

While only three of these features have shown significance in the outcomes, many more conclusions can be deducted. Several features aim to reduce the burden of diabetes management on the user or their caregivers without sacrificing good diabetes management. Therefore, it is important to point out that several features that aim to automate parts of diabetes management did not lead to significantly worse outcomes for their users. For example, the unannounced meals feature reduces the burden on the user to calculate and input meal bolus before a meal based on the amount of carbohydrates they are consuming. This study looked at 74 patients, of which 43 used the unannounced meal feature. The lack of significant differences between the two groups shows the effectiveness of this feature in a real-world setting. The use of DIYAPS has benefits beyond just glycemic outcomes. While this study has investigated glycemic outcomes, further studies need to investigate the impact on users' quality of life for various features. Furthermore, due to the susceptibility to type II errors of the non-parametric statistical tests used in this study, more data is needed to make reliable statements about the features where we could not reject the null hypothesis.

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