Incorporation of Mobile Application (App) Measures Into the Diagnosis of Smartphone Addiction

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ABSTRACT

Objective: Global smartphone expansion has brought about unprecedented addictive behaviors. The current diagnosis of smartphone addiction is based solely on information from clinical interview. This study aimed to incorporate application (app)-recorded data into psychiatric criteria for the diagnosis of smartphone addiction and to examine the predictive ability of the app-recorded data for the diagnosis of smartphone addiction.

Methods: Smartphone use data of 79 college students were recorded by a newly developed app for 1 month between December 1, 2013, and May 31, 2014. For each participant, psychiatrists made a diagnosis for smartphone addiction based on 2 approaches: (1) only diagnostic interview (standard diagnosis) and (2) both diagnostic interview and app-recorded data (app-incorporated diagnosis). The app-incorporated diagnosis was further used to build app-incorporated diagnostic criteria. In addition, the app-recorded data were pooled as a score to predict smartphone addiction diagnosis.

Results: When app-incorporated diagnosis was used as a gold standard for 12 candidate criteria, 7 criteria showed significant accuracy (area under receiver operating characteristic curve [AUC] > 0.7) and were constructed as app-incorporated diagnostic criteria, which demonstrated remarkable accuracy (92.4%) for app-incorporated diagnosis. In addition, both frequency and duration of daily smartphone use significantly predicted app-incorporated diagnosis (AUC = 0.70 for frequency; AUC = 0.72 for duration). The combination of duration, frequency, and frequency trend for 1 month can accurately predict smartphone addiction diagnosis (AUC = 0.79 for app-incorporated diagnosis; AUC = 0.71 for standard diagnosis).

Conclusions: The app-incorporated diagnosis, combining both psychiatric interview and app-recorded data, demonstrated substantial accuracy for smartphone addiction diagnosis. In addition, the app-recorded data performed as an accurate screening tool for app-incorporated diagnosis.

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The excessive use of smartphones has become a substantial worldwide social issue due to increasing smartphone penetration.[1–4] "Smartphone addiction" is considered to be a type of technological addiction. Griffiths[5] operationally defined technological addiction as a behavioral addiction that involves human-machine interaction and is nonchemical in nature. The most well-known behavior addiction, gambling disorder, has been categorized as a type of "substance-related and addictive disorder" in the *Diagnostic and Statistical Manual of Mental Disorders*, Fifth Edition (*DSM-5*).[6] A similar behavior pattern, internet gaming disorder, has also been listed in the research criteria of *DSM-5*.[6] The overwhelming global smartphone penetration has attracted increasing attention on smartphone addiction over the past years, leading to the development of several self-reported questionnaires and 2 mobile applications (apps).[7–12] Three core compulsive symptoms—"smartphone use for a period longer than intended," "recurrent failure to resist the impulse to use," and "use despite knowledge of having a persistent or recurrent physical or psychological problem"—were identified by the diagnostic criteria for smartphone addiction.[12] These symptoms are shared by individuals with substance use and gambling disorders.[6] Generally, smartphone addiction consists of 4 main components—compulsive symptoms, tolerance, withdrawal, and functional impairment[11]—which are identical to the components of internet addiction.[13] Among the 4 components, compulsive symptoms and tolerance, which manifest as excessive use and increasing use, respectively, can be quantified by smartphone-use data. Specifically, excessive use of smartphones can be quantified by duration and frequency for daily use count, and increasing use can be quantified by the trend of the duration. Lin et al[12] parameterized daily smartphone use data and demonstrated that these parameters were significantly associated with the diagnosis made by psychiatrists for smartphone addiction (psychiatric diagnosis).

The psychiatric diagnoses for all psychiatric disorders currently depend on the information provided by individuals. However, the information is subjective and sometimes insufficient for accurate diagnosis. For example, the use time reported by individuals with smartphone addiction is substantially lower than the actual use time.[12] The underestimate of use time decreases the sensitivity of psychiatrists' diagnosis

and can be corrected by app-recorded data. In addition, frequent short-period use is one important characteristic of smartphone addiction but is uncommon among other substance or behavior addictions. Although frequent short-period use is difficult to estimate from an individual's report,[11,12] it can be easily and accurately recorded by an app placed on the smartphone. Therefore, app-recorded data are necessary for accurate diagnosis of smartphone addiction. To our knowledge, no study incorporated app-recorded data into the standard psychiatric diagnosis of smartphone addiction.

In this study, we aimed to incorporate app-recorded data into psychiatric diagnosis for smartphone addiction and to build new diagnostic criteria. We also aimed to examine the predictive ability of the app-recorded data on the diagnosis of smartphone addiction. This study moved the diagnosis process from the standard psychiatric diagnosis to the app-incorporated diagnosis.

Clinical Points

- Smartphone-use patterns such as frequency and duration can be accurately measured in diagnostic interviews for smartphone addiction.
- Self-reported duration for smartphone use is underestimated compared with the app-recorded information. The app developed by our team can be considered as an accurate measurement tool. It not only increases the diagnostic accuracy, but also helps users to be aware of the actual time that they have spent on the smartphone.

METHODS

Participants

In total, 79 young adults were recruited from the Department of Electrical Engineering and the Department of Computer and Communication Engineering at 2 universities in Northern Taiwan between December 1, 2013, and May 31, 2014. Among these, 57 were male and 22 were female, with a mean ± SD age of 22.4 ± 2.3 years. Male college students are a high-risk population for internet addiction, which is similar to smartphone addiction. Therefore, the potential high-risk group was selected to enhance the power in this study.[14]

All participants used a smartphone with an Android operating system. A novel app developed by Lin et al[12] was installed on the smartphones of all participants to record smartphone use for 3 to 4 weeks. After the researchers checked the app data, each participant was interviewed and diagnosed for smartphone addiction by psychiatrists. The study was approved by the Institutional Review Board of the National Taiwan University Hospital, Taipei. All participants gave informed consent before entrance into the study, and all clinical investigations were conducted according to the principles expressed in the Declaration of Helsinki.

The App-Generated Parameters

The app recorded the screen-on and screen-off conditions of the smartphone (app-recorded data) without interrupting the smartphone operation or impacting the battery life. The measure of smartphone use from screen-on to the successive screen-off was defined as 1 epoch. This app calculated the mean daily epoch count for 1 month as the frequency parameter. Similarly, the mean daily epoch length and the mean daily median epoch duration were calculated as the duration and median parameters, respectively. The app also generated 3 trend-related parameters: F-trend, D-trend, and M-trend, from the trends of the frequency, duration, and median parameters, respectively (Figure 1). These trends were calculated via empirical mode decomposition analysis[15,16] because the measurement of fluctuations in smartphone use usually consisted of multiple periodic components and may increase in a nonstationary and/or nonlinear manner. The detailed algorithm for empirical mode decomposition analysis was described previously.[12,15,16]

Incorporating App-Generated Parameters Into Psychiatrists' Diagnostic Interview

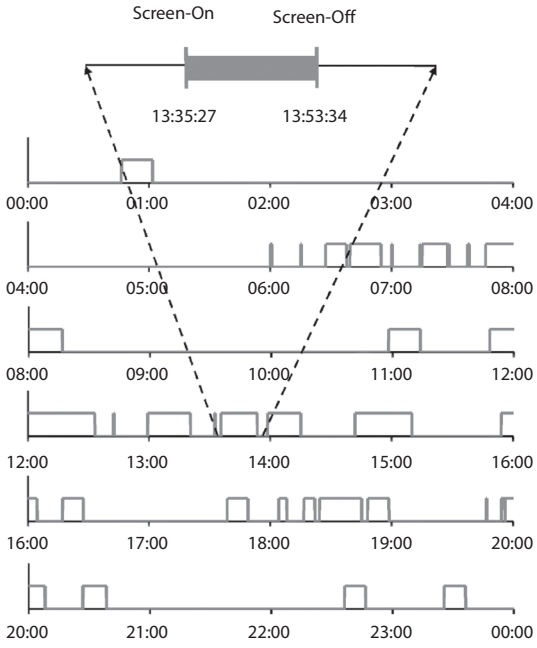
The proposed candidate diagnostic criteria for smartphone addiction consisted of 2 main sections, the symptoms criteria (criteria A) and functional impairment criteria (criteria B) (Table 1). In addition, criterion C, the exclusion criterion, excluded the smartphone use that resulted from major psychiatric disorders, which was the default criterion and would not be examined in the analysis. No participant was excluded from this study due to any major psychiatric disorder. In our previous study,[12] 12 candidate diagnostic criteria were proposed in criteria A (the characteristic symptoms of smartphone addiction) based on the diagnostic criteria of internet addiction for college students (DC-IA-C)[17,18] and on the research diagnostic criteria of the internet gaming disorder in the *DSM-5*.[6] All criteria were assessed in 2 ways: (1) both the app-generated parameters and the psychiatrists' diagnostic interviews ($criterion_{app}$) and (2) only the psychiatrists' diagnostic interviews ($criterion_{psy}$). For example, the $criterion_{psy}$ A3 indicated the criterion A3 (tolerance) assessed with solely psychiatrists' diagnostic interviews. In this study, 2 $criteria_{app}$, excessive use ($criterion_{app}$ A7, Table 1) and tolerance ($criterion_{app}$ A3, Table 1), were determined by the app-generated parameters instead of the psychiatrists' interviews. Based on our previous findings,[12] excessive use ($criterion_{app}$ A7) was defined as the frequency parameter greater than 68.4 count/day, and tolerance ($criterion_{app}$ A3) was defined as the M-trend parameter greater than zero.

Three qualified psychiatrists, who were experienced in substance and internet addiction disorders, interviewed all 79 participants. The interview process was recorded by video. During the interview, 2 kinds of app information were provided for psychiatrists' reference: (1) the extent of the participants' underestimation of daily smartphone use duration (ΔD, ie, the difference of self-estimated duration (D_{self}) and app-recorded duration (D_{app}) and (2) the tolerance and excessively frequent use defined by the app-generated parameters (ie, the M-trend and frequency parameters). After the interview, psychiatrists made a diagnosis regarding

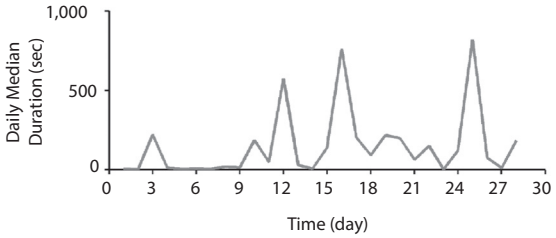
Figure 1. Visual Representation of the Data Generated by the Mobile Application (App)[a]

(A) The epoch starts with the screen-on (from 13:35:27) and ends with the screen-off (13:53:34). The duration of this use epoch is 1,087 seconds.

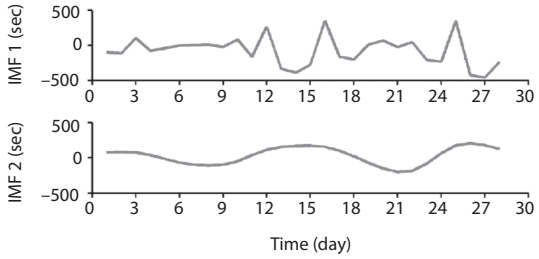
(B) One-day raw data in a subject: there are 33 epochs in this day (frequency = 33), and the total duration of the 33 epochs is 20,865 seconds. Among the 33 epochs, the epoch with the median duration is magnified into (A), that is, the median duration is 1,087 seconds.



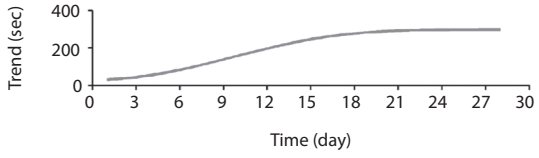
(C) Time series of daily median smartphone use duration over 28 days.



(D) The input is raw data, and it is outputted as intrinsic mode functions (IMF; IMF 1–2).



(E) Residual component (overall trend), and this M-trend = 8.7 seconds per day. The psychiatrist made the "app-incorporated diagnosis" based on the diagnostic interview and 3 app-generated parameters: the mean frequency, duration over 1 month, and the M-trend.



[a](A) and (B) demonstrate the raw data of smartphone use for 1 day. (C), (D), and (E) show the trend of the daily median use (M-trend) for 1 month decomposed by the empirical decomposition method.

smartphone addiction (app-incorporated diagnosis), according to their clinical experiences and the concepts of addiction proposed by West.[19] In contrast to app-incorporated diagnosis, standard diagnosis indicated the diagnosis for smartphone addiction made by psychiatrists without the app information. Because only 1 psychiatrist interviewed 1 participant at a time, the other 2 psychiatrists made their own standard diagnosis and app-incorporated diagnosis after viewing the video of the diagnostic interview. The interrater reliability for app-incorporated diagnosis (and 12 candidate criteria) was measured by Fleiss κ. The test-retest reliability was measured by the agreement between app-incorporated diagnosis and standard diagnosis ($criterion_{app}$ vs $criterion_{psy}$).

The sensitivity, specificity, and diagnostic accuracy of each $criterion_{app}$ and $criterion_{psy}$ in criteria A were analyzed using the app-incorporated diagnosis and the standard diagnosis as the gold standard, respectively. The $criteria_{app}$

Table 1. Validity and Reliability of the Candidate Diagnostic Criteria for Smartphone Addiction

Criterion		Proportion,[a] %	Diagnostic Accuracy,[a] %	Sensitivity,[a] %	Specificity,[a] %	Positive Predictive Rate,[a] %	Negative Predictive Rate,[a] %	Interrater Reliability[b] (κ), %	Test-Retest Reliability[c] (Agreement), %
A1	Preoccupation with smartphone use, and hence, keeping smartphone available all day	21.5	73.4	42.9	90.2	70.6	74.2	100.0	98.7
A2	Recurrent failure to resist the impulse to use the smartphone	30.4	79.7	64.3	88.2	75.0	81.8	81.1	96.2
A3	Tolerance: increase the median duration of the daily use epoch (M-trend > 0) within the past 1 month	39.2	50.6	35.7	58.8	32.3	62.5	100.0	57.0
A4	Withdrawal: manifested as a dysphoric mood, anxiety, and irritability after a period without smartphone use	31.6	75.9	60.7	84.3	68.0	79.6	100.0	94.9
A5	Smartphone use for a period longer than intended	32.9	74.7	60.7	82.4	65.4	79.2	81.5	97.5
A6	Persistent desire and/or unsuccessful attempts to cut down or reduce smartphone use	19.0	68.4	32.1	88.2	60.0	70.3	54.4	98.7
A7	Excessively frequent smartphone use: daily use frequency (F-trend) > 68.4 count/d	46.8	70.9	75.0	68.6	56.8	83.3	100.0	65.8
A8	Excessive effort spent on smartphone use as much as he/she can do	48.1	69.6	75.0	66.7	55.3	82.9	64.4	98.7
A9	Continued excessive smartphone use despite knowledge of having a persistent or recurrent physical or psychological problem	31.6	81.0	67.9	88.2	76.0	83.3	79.3	93.7
A10	Use of the smartphone to escape or relieve a dysphoric mood (eg, helplessness, guilt, anxiety)	19.0	73.4	39.3	92.2	73.3	73.4	54.4	100.0
A11	Loss of previous interests, hobbies, and entertainment as a result of, and with the exception of, smartphone use	16.5	65.8	25.0	88.2	53.8	68.2	83.1	98.7
A12	Has deceived family members, therapists, or others regarding the time spent on smartphone use	8.9	63.3	10.7	92.2	42.9	65.3	77.5	100.0
B1	Functional impairment	49.4	81.0	92.9	74.5	66.7	95.0	100.0	100.0
B2	Excessive smartphone use is significantly time-consuming	24.1	75.9	50.0	90.2	73.7	76.7	89.6	96.2

[a]The measurements of $criteria_{app}$ with app-incorporated diagnosis as gold standard.
[b]The interrater reliability of $criteria_{app}$ measured by different psychiatrists.
[c]The agreement between $criteria_{app}$ and $criteria_{psy}$.
Abbreviations: F-trend = trend parameter related to frequency of use, M-trend = trend parameter related to daily median use.

with high diagnostic accuracy were called the validated diagnostic criteria and were summed as a score (the criteria score). The cutoff point of the criteria score for smartphone addiction diagnosis was determined by the best diagnostic accuracy.

The Predictive Ability of the App-Generated Parameters for Smartphone Addiction Diagnosis

Using standard diagnosis and app-incorporated diagnosis as the gold standard, we evaluated the predictive ability of 6 app-generated parameters (the frequency, duration, median, F-trend, D-trend, and M-trend parameters) for smartphone addiction. The association between smartphone addiction diagnosis and each parameter was quantified by the area under receiver operating characteristic curve (ie, AUC). For the joint predictive ability of these parameters, we fitted a logistic regression model to pool the information of parameters that were significantly associated with smartphone addiction. In this model, app-generated parameters were the predictors, and smartphone addiction diagnosis (standard or app-generated diagnoses) was the dependent variable. For example, if p parameters were significantly associated with smartphone addiction diagnosis, the corresponding regression model was $\text{logit}\ \Pr[\text{smartphone addiction diagnosis}] = \beta_0 + \beta_1 \times (\text{parameter}\ \ 1) + \beta_2 \times (\text{parameter}\ 2) + \ldots + \beta_p \times (\text{parameter p})$. Here, β_0 was the intercept and β_1, β_2, ..., and β_p were the regression coefficients for the corresponding app-generated parameters. The maximal likelihood estimates for all coefficients for each participant were calculated. Then, the predictive probability of smartphone addiction for each individual was defined as the risk score, which could be generated by the following formula: $[1 + \exp(-\beta_0 - \beta_1 \times \text{parameter}\ \ 1 - \beta_2 \times \text{parameter}\ 2 - \ldots - \beta_p \times \text{parameter p})]^{-1}$.

Table 2. Diagnostic Accuracy, Sensitivity, and Specificity for Different Cutoff Points of the Criteria Score

Cutoff Point	Diagnostic Accuracy, %	Sensitivity, %	Specificity, %	Positive Predictive Rate, %	Negative Predictive Rate, %
1	58.2	100.0	35.3	45.9	100.0
2	83.5	100.0	74.5	68.3	100.0
3	92.4	92.9	92.2	86.7	95.9
4	81.0	53.6	96.1	88.2	79.0
5	75.9	35.7	98.0	90.9	73.5
6	69.6	17.9	98.0	83.3	68.5
7	68.4	10.7	100.0	100.0	67.1

In this case, the app-incorporated diagnosis was the dependent variable and 3 parameters (the duration, frequency, and F-trend parameters) were predictors. The risk score was $[1+\exp(-\beta_0-\beta_{duration}\times duration-\beta_{frequency}\times frequency-\beta_{F\text{-}trend}\times F\text{-}trend)]^{-1}$. The predictive ability of this score for smartphone addiction was quantified by AUC. All above statistical analyses were performed under R 3.0 software (https://www.R-project.org).

RESULTS

The agreements of "tolerance" ($criterion_{app}$ A3 vs $criterion_{psy}$ A3) and "excessively frequent use" ($criterion_{app}$ A7 vs $criterion_{psy}$ A7) were 57.0% and 65.8%, respectively, while the agreements of the other candidate criteria ranged from 93.7% to 100% (Table 1). The agreement between the standard diagnosis and app-incorporated diagnosis was 87.3% (ie, 10 subjects have inconsistent assessment between the standard diagnosis and app-incorporated diagnosis). The proportions of smartphone-addictive participants defined by the standard diagnosis and app-incorporated diagnosis were the same (28 and 51 participants were classified as smartphone addiction positive and smartphone addiction negative groups, respectively). The interrater reliability of app-incorporated diagnosis was 0.805.

The specificity, sensitivity, and diagnostic accuracy for the 12 candidate diagnostic $criteria_{app}$ for app-incorporated diagnosis are also shown in Table 1. The diagnostic accuracy for the 12 $criteria_{app}$ ranged from 50.6% to 81.0%. The diagnostic accuracies of criterion A3 "tolerance" (50.6%), criterion A6 (68.4%), criterion A8 (69.6%), criterion A11 (65.8%), and criterion A12 (63.3%) were relatively low compared to the other 7 criteria (the validated diagnostic criteria), which ranged from 70.9% to 81.0%. Therefore, these 5 diagnostic criteria were excluded from the further analyses.

The cutoff point for the criteria score (the sum of 7 validated diagnostic criteria) was determined by analyzing the diagnostic accuracy for each cutoff point (Table 2). The results revealed that a cutoff point at 3 (ie, the participants with 3 criteria or more were diagnosed with smartphone addiction) showed the best diagnostic accuracy (92.4%). When functional impairment (criterion B1) was added to the 7 validated diagnostic criteria, a cutoff point of 3 demonstrated a higher diagnostic accuracy (93.7%, not shown in Tables). The proposed diagnostic criteria for smartphone addiction are listed in Table 3. Criteria A consisted of the 7 characteristic symptoms of smartphone addiction and criteria B described the functional impairment and subjective distress due to smartphone use. According to the proposed diagnostic criteria, 27 participants were diagnosed as having smartphone addiction (ie, the app-incorporated diagnosis).

Table 4 shows the AUC for the 6 app-generated parameters. The frequency parameter was significantly associated with both diagnoses of smartphone addiction (AUC = 0.70 for app-incorporated diagnosis and AUC = 0.63 for standard diagnosis). The duration parameter was significantly associated with the app-incorporated diagnosis (AUC = 0.72), but not with the standard diagnosis (AUC = 0.61). The median and F-trend parameters were only associated with app-incorporated diagnosis and standard diagnosis, respectively. Consequently, we applied 3 app-generated parameters—frequency, duration, and F-trend—to predict smartphone addiction diagnosis by fitting the logistic regression model. Although associated with standard diagnosis only, the F-trend parameter was still included in the next analysis because it represented the trend of increasing smartphone use. The maximal likelihood estimates of coefficients for 3 parameters were derived and pooled as a risk score (Table 5). The AUC of the risk score for both standard and app-incorporated diagnoses were greater than 0.70 (Table 5).

DISCUSSION

To our knowledge, this is the first study to propose and validate the app-incorporated diagnostic criteria for smartphone addiction. We used the same sample but different diagnostic processes to compare the app-incorporated diagnosis in the present study and the standard diagnosis in our previous study.[12] The diagnostic accuracy of app-incorporated diagnosis reached to 92.4% (with criteria A only) and 93.7% (with both criteria A and B), higher than the accuracy of standard diagnosis (87.3%), which is based solely on participants' recall of smartphone use. In addition, with similar methodology to validate the diagnostic criteria, our results not only highlighted the importance of app-generated parameters for an accurate psychiatric diagnosis, but also verified the reliability of each diagnostic criterion between both diagnostic processes (Table 1). This is also the first study to reveal the predictive ability of the app-generated parameters for smartphone addiction diagnosis. Our findings indicated that the duration and frequency of daily smartphone use and the frequency trend (the duration, frequency, and F-trend parameters) were able to significantly predict smartphone addiction diagnosis.

We defined excessive use (criterion A7) based on the frequency parameter, rather than the duration parameter. Although excessive use is defined by high frequency and long duration of smartphone use, no significant association has been shown between the duration parameter and smartphone addiction.[12] A pilot study[10] also demonstrated

Table 3. Proposed App-Incorporated Diagnostic Criteria for Smartphone Addiction

Criterion No.	Definition
A	**Maladaptive pattern of smartphone use, leading to clinically significant impairment or distress, occurring at any time within the same 3-month period. Three (or more) of the following symptoms having been present:**
1	Preoccupation with smartphone use, and hence keeping smartphone available all day
2	Recurrent failure to resist the impulse to use the smartphone
3	Withdrawal: as manifested by a dysphoric mood, anxiety, and/or irritability after a period without smartphone use
4	Smartphone use for a period longer than intended
5	Excessively frequent smartphone use: daily use frequency > 68.4 count/d
6	Continued excessive smartphone use despite knowledge of having a persistent or recurrent physical or psychological problem caused by smartphone use
7	Use of the smartphone to escape or relieve a dysphoric mood (eg, helplessness, guilt, anxiety)
B	**Functional impairment**
1	Functional impairment: 1 (or more) of the following symptoms have been present
(1)	Excessive smartphone use resulting in a persistent or recurrent physical or psychological problem
(2)	Smartphone use in situations in which it is physically hazardous (eg, smartphone use during driving or crossing the street)
(3)	Has jeopardized or lost a significant relationship, job, or educational/career opportunity because of smartphone use
2	Excessive smartphone use causes significant subjective distress, or is time-consuming
C	**Exclusion criteria: The smartphone addictive behavior is not better accounted for by obsessive-compulsive disorder or by bipolar I disorder**

Table 4. AUC Analysis of the App-Generated Parameters for Smartphone Addiction Diagnosis Based on 2 Diagnostic Approaches

App-Generated Parameter	App-Incorporated Diagnosis		Standard Diagnosis	
	AUC (95% CI)	*P* Value	AUC (95% CI)	*P* Value
Frequency	0.70 (0.58–0.83)	.003*	0.63 (0.51–0.76)	.047*
F-trend	0.57 (0.45–0.70)	.280	0.63 (0.51–0.76)	.050*
Duration	0.72 (0.60–0.84)	.001*	0.61 (0.48–0.74)	.110
D-trend	0.53 (0.40–0.66)	.645	0.53 (0.40–0.67)	.609
Median	0.65 (0.53–0.77)	.029*	0.58 (0.45–0.77)	.228
M-trend	0.53 (0.40–0.66)	.708	0.57 (0.44–0.69)	.287

*P value < .05.
Abbreviations: AUC = area under receiver operating characteristic curve, CI = confidence interval, D-trend = trend parameter related to duration of use, F-trend = trend parameter related to frequency of use, M-trend = trend parameter related to daily median use.

Table 5. Logistic Regression Model for Different Definition of Smartphone Addiction and the AUC of Risk Score

Variable	App-Incorporated Diagnosis		Standard Diagnosis	
	Estimate	*P* Value	Estimate	*P* Value
Regression coefficient for app-generated parameters (SE)				
Intercept	−3.523 (0.915)	< .001*	−2.255 (0.716)	.002*
Duration	0.312 (0.138)	.024*	0.148 (0.123)	.137
Frequency	0.02 (0.009)*	.019*	0.008 (0.006)	.149
F-trend	1.092 (0.733)	.136	1.69 (0.816)	.080
AUC (95% CI) of the risk score	0.79 (0.68–0.89)	< .001*	0.71 (0.59–0.83)	.002*

*P value < .05.
Abbreviations: AUC = area under receiver operating characteristic curve, CI = confidence interval, F-trend = trend parameter related to frequency of use, SE = standard error.

that the scores of the Korean Smartphone Addiction Scale were correlated to daily use frequency but not duration. Our study demonstrated that the frequency parameter robustly predicted both standard and app-incorporated diagnoses of smartphone addiction. Among all substance and behavior addictions, it is the frequent short-period use, rather than long-term use, specific to smartphone addiction that interferes with daily routine activity and thus results in functional impairment. For example, 1 previous study[20] showed that texting, internet surfing, and phone reaching increased the risk of motor vehicle crash or near-crash. Although the "excessively frequent smartphone use" (criterion A7) showed the lowest diagnostic accuracy (70.9%) among the validated criteria A (70.9%–81.0%, Table 1), this criterion had the highest sensitivity (75.0%) among criteria A, in contrast to other criteria (from 39.3% to 67.9%). It was also the only criterion with sensitivity higher than specificity. The high sensitivity implied that this criterion can be used as an efficient screening tool for smartphone addiction. Moreover, since the criterion is generated by the app automatically, it will substantially decrease the cost of large-scale screening. In contrast, the duration parameter showed higher specificity and significant predictive ability for the app-incorporated diagnosis rather than standard diagnosis. The results confirmed our previous findings that underestimation dampened the predictive ability of duration,[12] demonstrating the necessity of app-incorporated diagnosis for diagnostic accuracy.

Similar to findings in previous published studies, tolerance (criterion A3: increasing M-trend) failed to predict smartphone addiction (Table 2), which implied that tolerance may not be the core component in smartphone addiction, which was also supported by previous studies.[9,11] The other explanation was that the app record for 1 month might be insufficient to detect the trends for the tolerance measurement, which is generally defined within a minimum of 3 months. An alternative definition for this criterion as "a marked increase in the daily smartphone use count" (ie, F-trend > 0) can be considered in further studies. In the final regression model, frequency, duration (represents the excessive use), and F-trend parameters (represents the increasing use) precisely predicted smartphone addiction. The increasing use could be regarded as a form of tolerance or another core symptom "recurrent failure to resist the impulse to use the smartphone" (criterion A2). Even though the symptoms relevant to F-trend need to be further explored, the parameter automatically driven by the empirical mode decomposition analysis sophisticatedly delineated the trend

of smartphone use in a nonstationary and nonlinear manner within a period. The F-trend delineates the time course and serves as a useful tool to assess relapse of smartphone addiction, which can be difficult with psychiatric interview only. Relapse is a significant characteristic of substance and internet addiction, and relapse prevention is knotty in clinical practice.[13] Thus, F-trend can be regarded as an index of relapse, facilitating the prevention and treatment of smartphone addiction. The core symptoms proposed by our study indicated that smartphone addiction is a "recurrent failure to resist the impulse to the excessively frequent smartphone use, despite knowledge of having a persistent or recurrent physical or psychological problem" (according to criteria A2, A5, and A6 in Table 3), which matches the definition of addiction proposed by West,[19] except for the tolerance symptom.

Several methodological limitations should be noted when interpreting our findings. First, the fact that our study recruited college students only limited the generalization of our findings. Second, the epoch of smartphone use was defined by the screen-on to screen-off time. This definition cannot completely represent the status of smartphone use. More detailed information, such as how many and what kind of apps had been used by participants, should be identified in future studies. Furthermore, unlike substance use, smartphone use is not currently a legally problematic behavior. More studies should be conducted to investigate the social impact and burden caused by smartphone addiction. In addition, our app was based on the Android operating system. Various versions applicable to other operating systems such as iOS should be developed in the future. Finally, the 1-month record might not be enough to allow detection of trends in some significant parameters such as M-trend and should be extended to 3 months or more.[6]

In conclusion, the app-incorporated diagnosis demonstrated good accuracy for smartphone addiction diagnosis. Corresponding to 2 core symptoms (excessive use and increasing use), 3 app-generated parameters (the duration, frequency, and F-trend parameters) significantly predicted the diagnosis of smartphone addiction.

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